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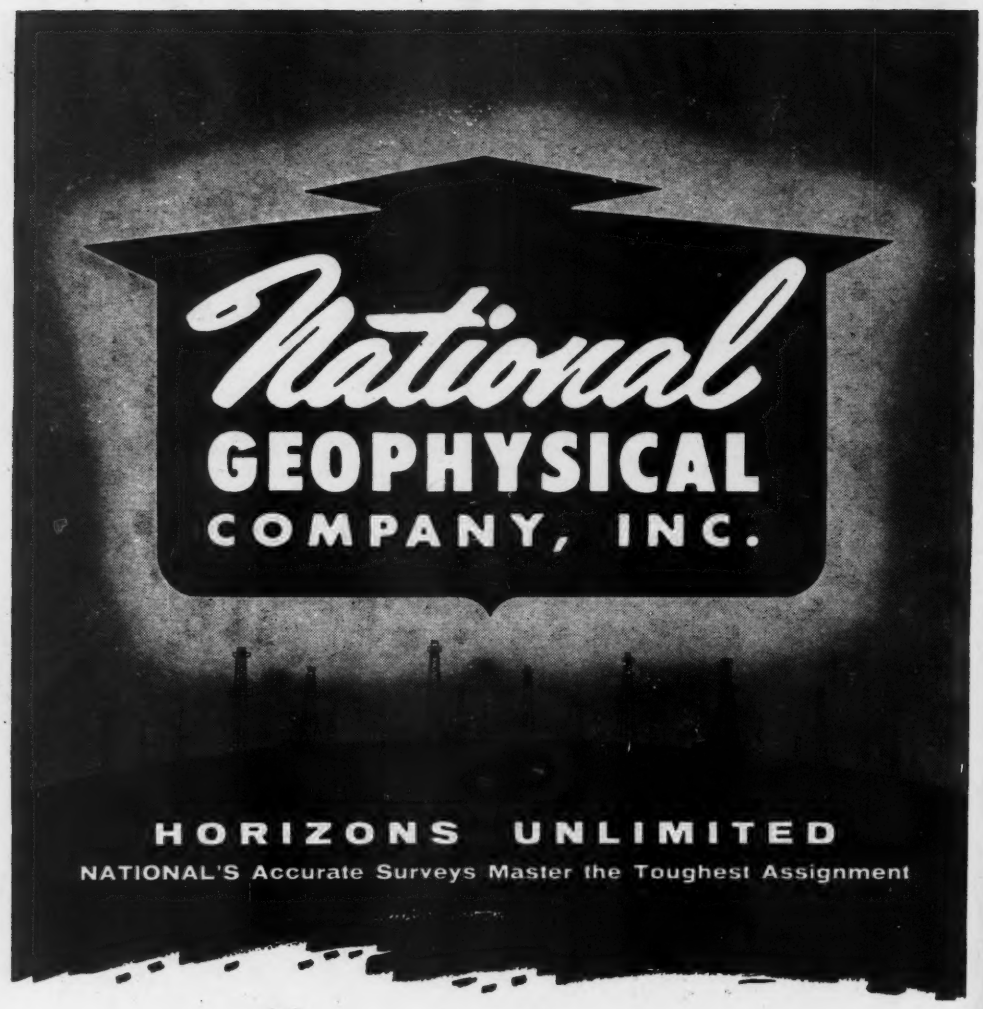

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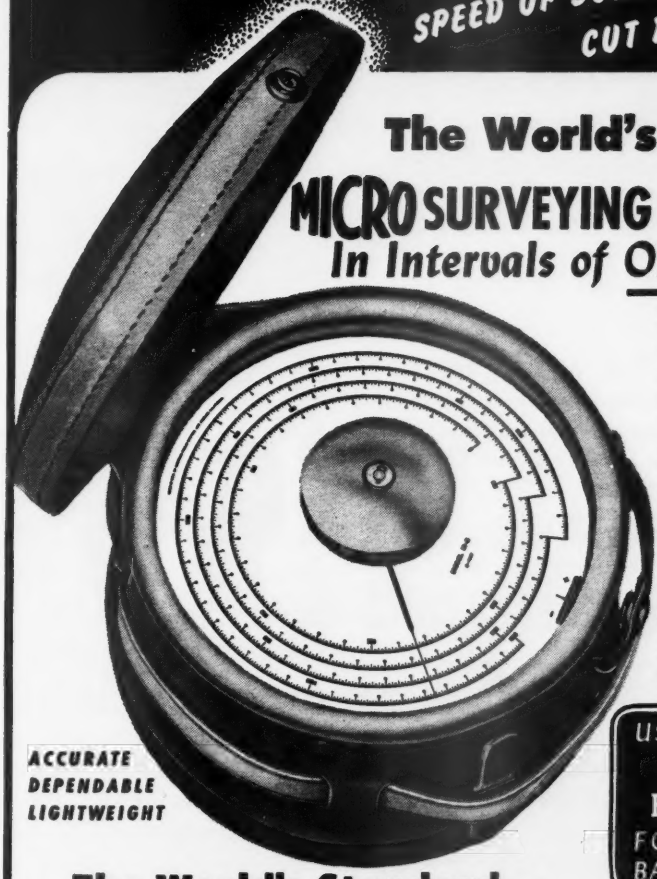

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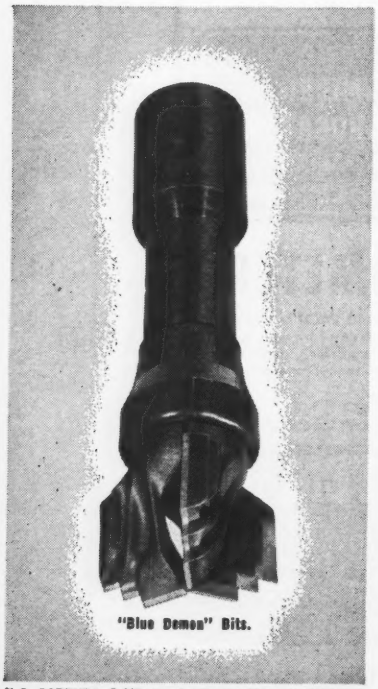

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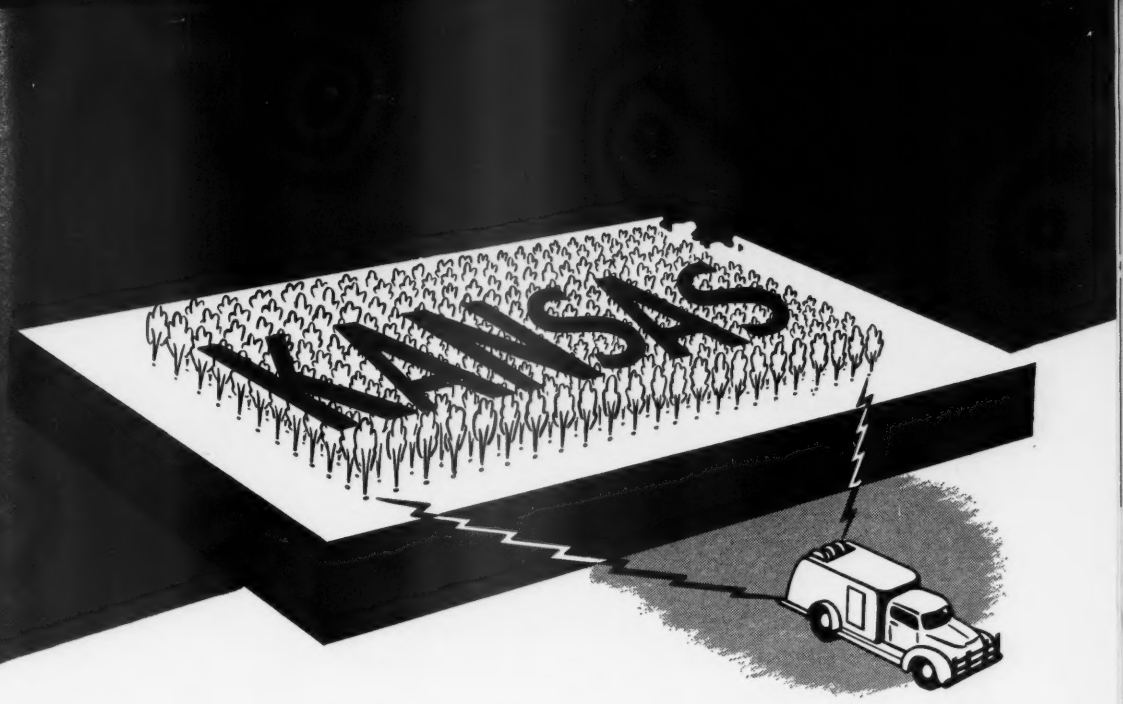

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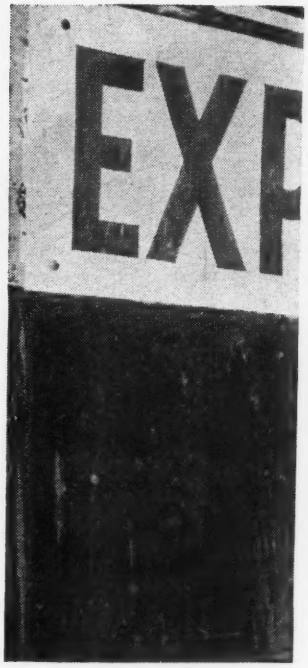

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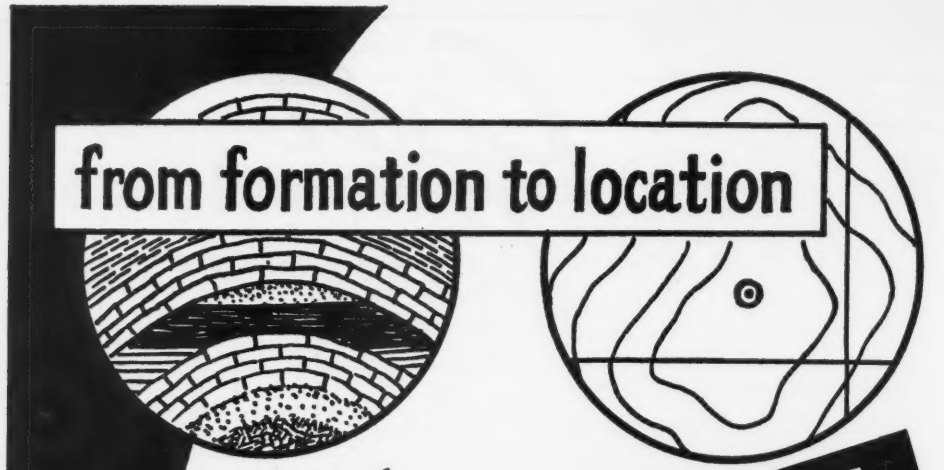

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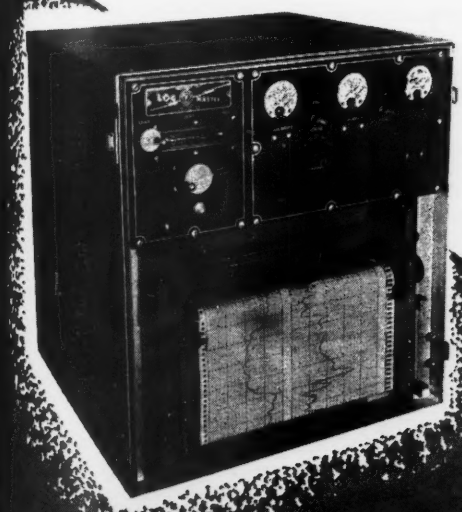

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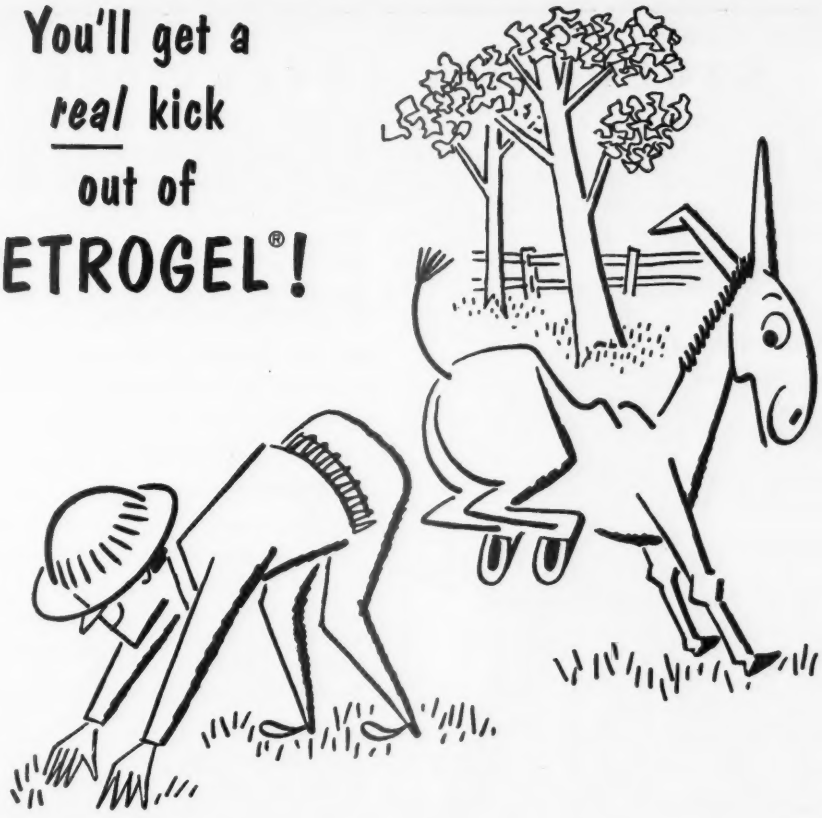

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GEOPHYSICS

TECHNICAL PAPERS

MAGNETIC DELAY LINE FILTERING TECHNIQUES*

HAL J. JONES,† JOHN A. MORRISON,† G. P. SARRAFIAN,†
AND L. J. SPIEKER†

ABSTRACT

Modern communications theory and information theory have placed considerable emphasis upon the problem of detection and extraction of signals in noise backgrounds. Some of the methods and equipment developed have possible geophysical applications. This paper presents a discussion of the delay line method of filter approximation. Magnetic recording delay line equipment which permits approximation of a wide variety of linear filtering and correlation operations is described. The fundamental theory of linear operator filtering by delay line techniques is outlined and some possible applications to processing seismic data are briefly discussed.

INTRODUCTION

The problem of separating desired signals from noise backgrounds has received intensive study in recent years, largely due to rapid progress made in modern communications theory and information theory. The importance of this problem in the recording and interpretation of geophysical data is well recognized. A considerable variety of methods is used to facilitate separation of signals by visual interpretation of field records; in seismic prospecting, for example, these include instrumental filtering by electrical networks, arrays of seismometers, compositing of outputs of seismometer stations, and compositing of seismometer outputs with various relative time delays. These methods all may be classified as general filtering operations, as illustrated schematically in Figure 1. In designing a filtering operation for a given problem, we try to select the characteristics of the "box" of Figure 1 so that a desired result is most nearly attained. This result may be the detection or extraction of a particular set of signals from the input data. Clearly, the nature of the "best" filter depends upon the problem

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being attacked and upon the information regarding signal and noise which is at our disposal.

A wide variety of filtering operations can be effected by sampling techniques involving discrete sampling of data, selective weighting of the samples, and averaging of the weighted samples. These may be designated as *linear operator* filtering methods. A thorough discussion of linear operator theory and techniques has been given by Smith (1954) and other workers at MIT. In this paper, we shall

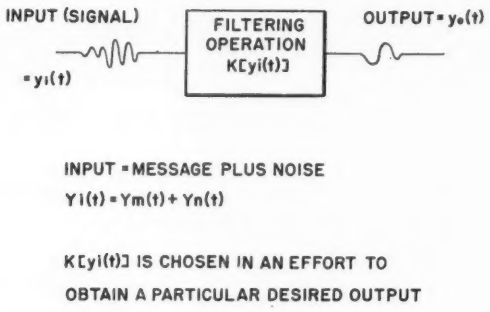
INPUT (SIGNAL)
= y₁(t)
FILTERING OPERATION K[yi(t)]
OUTPUT = y₀(t)
INPUT = MESSAGE PLUS NOISE
Yi(t) = Ym(t) + Yn(t)
K[yi(t)] IS CHOSEN IN AN EFFORT TO
OBTAIN A PARTICULAR DESIRED OUTPUT

FIG. 1. Schematic diagram of generalized filtering operation.

discuss the application of linear operator filtering to input data in electrical form by use of magnetic recording delay lines.

REVIEW OF LINEAR FILTER THEORY

We begin by reviewing some fundamentals of linear filter theory, closely following the treatment of Bode and Shannon (1950). Linear filtering operations commonly are described in two different but equivalent ways. The method most familiar to geophysicists employs a complex *frequency transfer function* $Y(\omega)$ which describes a filter in terms of its response to steady-state sine and cosine input signals. The transfer function is often written as

$$Y(\omega) = e^{A(\omega)}e^{iB(\omega)},$$

so that $A(\omega) = \log |Y(\omega)|$ is the gain of the filter and $B(\omega) = \text{angle } [Y(\omega)]$ is the phase characteristic.

The filter can also be described in terms of a *weighting* or *time function* $K(t)$. This function is simply the response of the filter to a unit impulse input applied at time $t = 0$. To get the response of the filter at time $t = t_1$ to an arbitrary input waveform $y(t)$, the waveform is broken down into impulses, and the contributions of the individual impulses are added as illustrated in Figure 2. At time t_1 each impulse will have a contribution $y(t)dtK(t_1 - t)$. Thus, the filter output $Z(t_1)$ at t_1 can be expressed mathematically as

$$Z(t_1) = \int_{-\infty}^{t_1} y(t)K(t_1 - t)dt. \tag{1}$$

In applying this formula, it is convenient to make the variable substitution $\tau = t_1 - t$ so that (1) becomes

$$Z(t_1) = \int_0^\infty y(t_1 - \tau)K(\tau)d\tau, \tag{2}$$

where τ represents the "age" of the data. Equation (2) is the familiar superposition integral.

The equivalence of the two methods of describing filters outlined above is

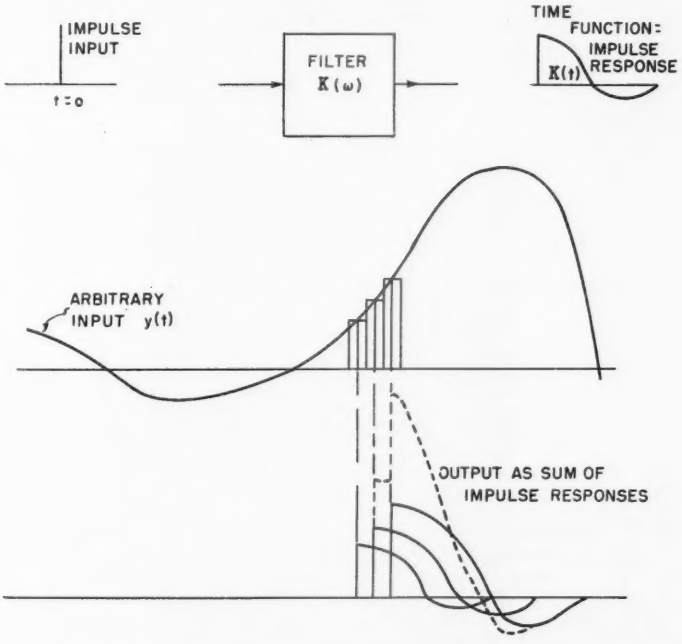

FIG. 2. Filter response to arbitrary input, synthesized from impulsive responses (Bode and Shannon, 1950).

demonstrated by stating the relationship of the weighting function and $Y(\omega)$ via the Fourier transform:

$$K(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} Y(\omega)e^{j\omega t}d\omega \tag{3}$$

$$Y(\omega) = \int_{-\infty}^{\infty} K(t)e^{-j\omega t}dt. \tag{4}$$

To insure physically realizable and stable filters, the following restrictions are imposed on $K(\tau)$:

1. $K(\tau) = 0$ for $\tau < 0$, i.e., the filter has no output before an input is applied.

2. $K(\tau) \to 0$ as $\tau \to \infty$, i.e., the effect of the remote past gradually dies out.

Equivalent criteria can, of course, be specified in the frequency domain. An interesting discussion of stability and physical realizability criteria for linear, passive, lumped-constant systems has recently been given by Gilbert (MIT, 1955).

DELAY LINE FILTERING

The use of magnetic delay lines and multiple pickup heads as illustrated in Figure 3 provides apparatus suitable for simulating a wide variety of filters. The

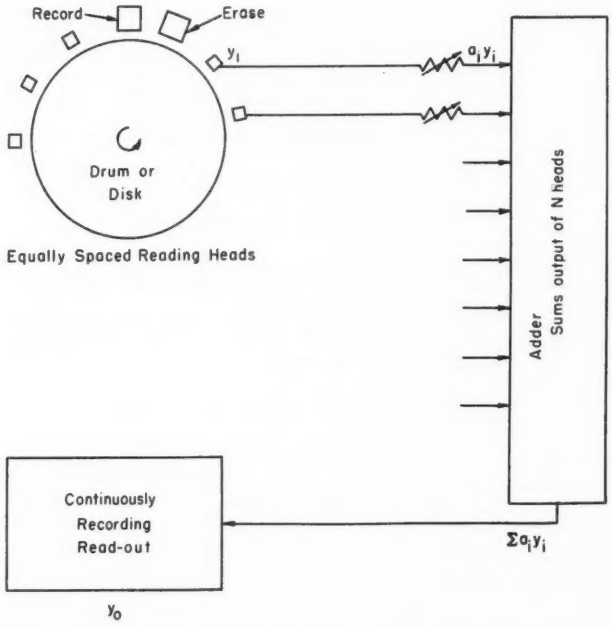

FIG. 3. Schematic diagram of delay line filter apparatus.

apparatus "models" equations (1) and (2) by sampling the input data at a series of regularly spaced time points, adjusting the amplitude of each sample individually, and averaging a number of samples. Equation (2) is replaced, then, by a summation formula

$$Z(t) = \sum_{K=1}^{M} a_K y(t - K\tau), \tag{5}$$

where

$Z(t) = Z(t_1) =$ continuous output

$\tau =$ data sampling interval

$y(t - K\tau) =$ continuous input sampled at points τ units apart

a_K = discrete values of weighting function at sampling points τ units apart

M = total number of samples in the filter operator.

The summation is from 1 to M in equation (5) since the first sampling point is always delayed by τ units from the recording head. In the drum-type apparatus of Figure 3, τ is determined by pickup-head spacing, and M is limited by elapsed

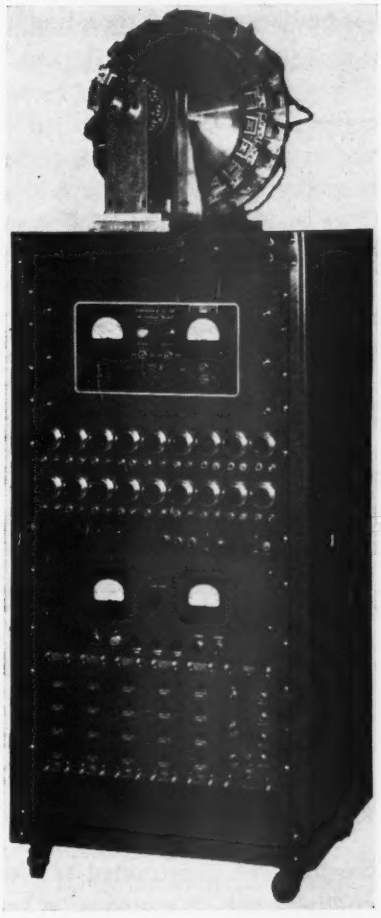

FIG. 4. Photograph of research-model delay line filter.

travel time between recording head and the pickup head adjacent to the erasing magnet. For evenly spaced heads

$$\tau = T/(M + 1)$$

where T is the period of revolution of the drum.

To simulate a particular filter we first determine its weighting function $K(t)$.

The a_K's in equation (5) are then the values of $K(t)$ at equally spaced sampling points and are obtained by adjusting potentiometer settings. The potentiometers effectively provide multiplication by a set of constants (each of which is less than unity). The individually attenuated outputs from the battery of pickup heads are instantaneously summed and read out, yielding a continuous filter output $Z(t)$. The filter operator a_K projects into the past of the input as equation (5) indicates, thus in the apparatus of Figure 3, the a_1 coefficient is applied to the signal from the pickup head adjacent to the recording head.

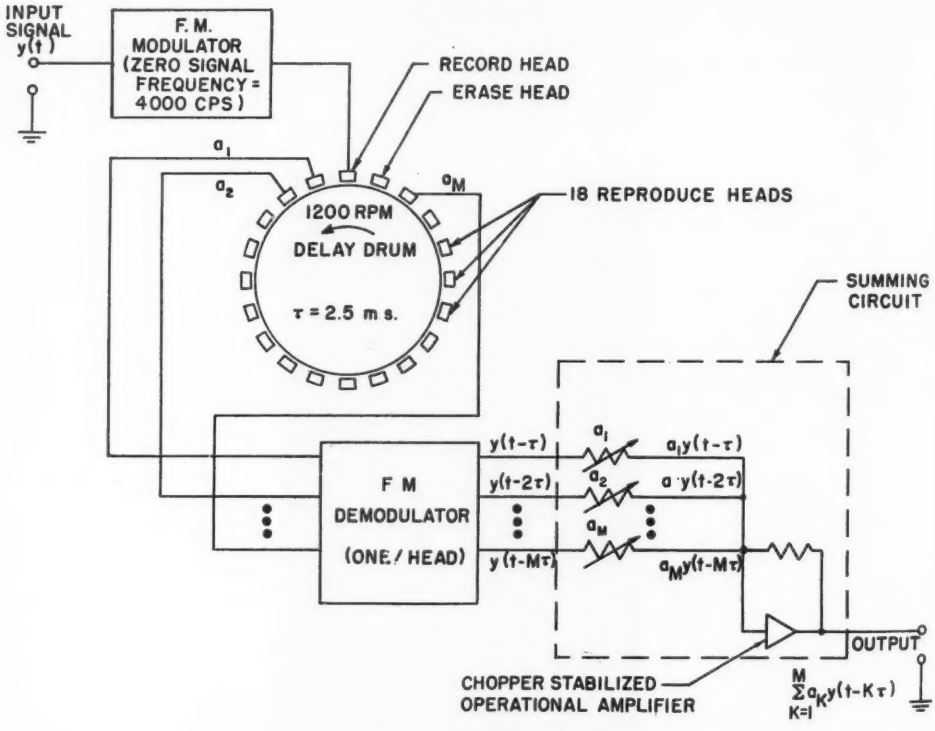

FIG. 5. Block diagram of research-model delay line filter.

The delay line filter equipment constructed at Texas Instruments is illustrated in Figure 4. A recording head, 18 reproducing heads, and an erasing magnet are evenly spaced around the periphery of a 10-inch diameter drum coated with red magnetic oxide. In normal operation the filter operator length is 45 milliseconds. An FM system of recording is employed with a 4-kc carrier and non-contact recording. In this method, signals impressed upon the drum surface are frequency-modulated square waves, recorded to saturation in both positive and negative directions. Signal strength and spectrum are insensitive to head-to-drum radial spacing over a relatively large range. This property relaxes somewhat the tolerances on drum concentricity and head-to-drum gap. Associated

electronics includes a recording head modulator, individual demodulators for each pickup head, individual potentiometers, and a summing amplifier. The last is a chopper-stabilized, d-c operational amplifier. Provision is made for sign reversal of outputs of individual pickup heads. Figure 5 is a block diagram of the apparatus shown in the photograph of Figure 4.

The single-channel unit may be used with the playback of a multitrace magnetic record by utilizing programmed sequential trace-by-trace playback. Once a file of filter response functions has been built up, changing filter settings is a simple matter of potentiometer dial adjustment. Ability of the system to simulate filters is, of course, restricted by the finite head spacing and limited operator length. The effect of these limitations will be discussed in the following sections. In addition, the system response imposes bounds on frequency and phase characteristics. It is necessary to insure that the frequency and phase characteristics of the system are flat over at least as great a range as the magnetic recorder on which original data are obtained. Further, the instantaneous dynamic range of the filter must be at least as large as that of the magnetic recorder. The research equipment illustrated in Figure 4 has an instantaneous dynamic range of more than 55 db (above instrumental noise level) and has a flat response from 4 cps to 300 cps.

The frequency range of operation of the device could be adjusted to a higher or lower band by speeding up or slowing down the drum; the sampling interval and operator duration would both be changed by such an adjustment. It is clear that delay line filters could be constructed by using relatively few movable heads and sampling, e.g., at the centroids of the half waves of the impulse response (Swartz and Sokoloff, 1954).

SIMULATION OF LINEAR FILTERS

By proper selection of the coefficient series a_K of equation (5) a wide variety of linear filtering operations may be simulated by a delay line apparatus. Some specific applications will be discussed following a few brief comments on theory.

Theory

If we take the Fourier transform of the delay line filter output as given by equation (5), we obtain the following expression for the spectrum $Z(\omega)$ of the output over the interval T_1 to T_2:

$$Z(\omega) = \int_{T_1}^{T_2} \sum_{K=1}^{M} a_K y(t - K\tau) e^{-j\omega t} dt. \tag{6}$$

The spectrum of the filter input $y(t-K\tau)$ is given by

$$Y(\omega) = \int_{T_1}^{T_2} y(t - K\tau) e^{-j\omega(t-K\tau)} dt. \tag{7}$$

Now, if we make the substitution $\epsilon=(t-K\tau)$, and multiply the right hand side by $e^{+K\tau}\cdot e^{-K\tau}=1$, equation (6) becomes

$$Z(\omega) = \int_{T_1}^{T_2} \sum_{K=1}^{M} a_K y(t-K\tau) e^{-j\omega(t-K\tau)} \cdot e^{-j\omega K\tau} dt$$

$$= \left[\sum_{K=1}^{M} a_K e^{-j\omega K\tau}\right] \int_{T_1}^{T_2} y(\epsilon) e^{j\omega\epsilon} d\epsilon \tag{8}$$

$$= \left[\sum_{K=1}^{M} a_K e^{-j\omega K\tau}\right] Y(\omega),$$

provided that the interval T_2-T_1 is large compared to the interval $M\tau$ and that

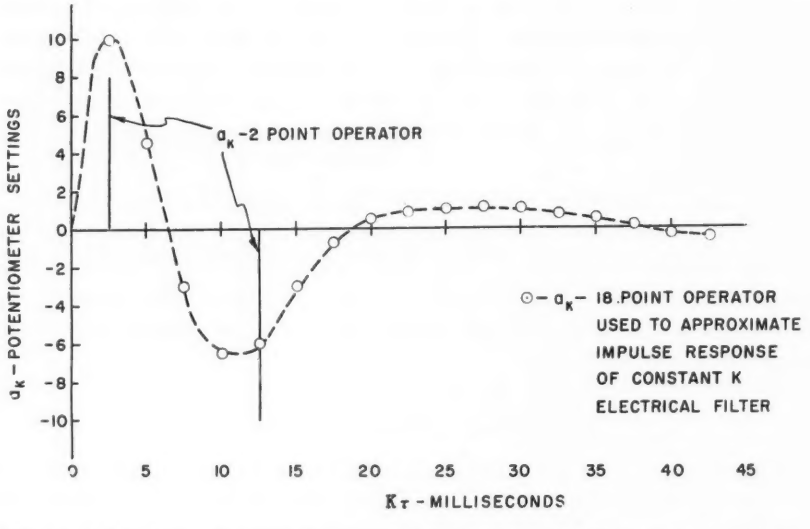

FIG. 6a. Delay line filter operator approximations to electrical filter impulse response.

the spectra change slowly with variation in time. Equation (8) is of the form

$$Z(\omega) = K(\omega)Y(\omega), \tag{9}$$

where the frequency transfer function of the delay line linear filter operator is

$$K(\omega) = \sum_{K=1}^{M} a_K e^{-j\omega K\tau}. \tag{10}$$

The characteristics of $K(\omega)$ have been discussed in detail by workers at MIT (Smith, 1954; Wadsworth et al., 1953), and our comments will be limited to the special case of symmetric operators to be discussed below. Our aim is to stress the nature and possible applications of delay line filter techniques rather than to present a detailed theoretical treatment.

Simulation of Conventional Seismic Filters

Electric wave filters of the type generally used in seismic recording amplifiers are readily simulated by the delay line. The a_K coefficient series is determined by taking samples of the filter impulse response. Figures 6b and 6c illustrate use of the delay line to model an electrical filter whose impulse response is shown in 6a. Delay line output for various operator approximations is compared with electrical filter output for a seismic trace input signal. Note that in this example, a two point operator produced a satisfactory approximation. Figure 7 compares the frequency response of the delay line models with that of the electrical filter.

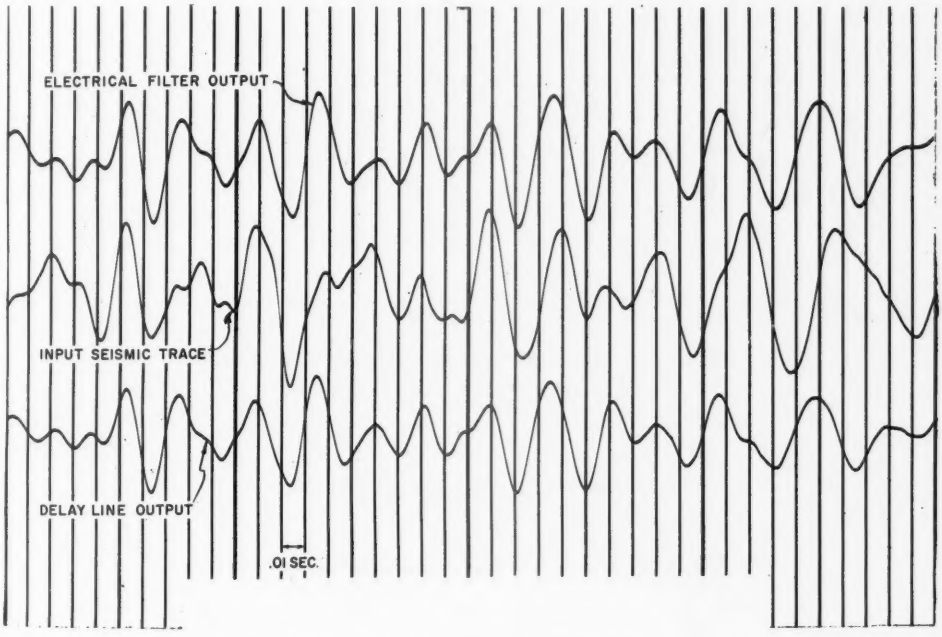

FIG. 6b. Comparison of seismic trace filtered by electrical filter and by 18-point delay line operator.

These examples show that the action of typical electrical filters can be duplicated by delay line techniques. Tests of conventional electrical filters used in seismic amplifiers indicate that constant K type filters often can be simulated with 2 or 3 properly weighted and spaced sampling points and that 5 or 6 sampling points are adequate to model many M-derived type filter networks. When used to simulate physically realizable filters in this manner, the delay line filter delays the output by a small constant amount not greater than the head spacing τ.

Approximation of Ideal Filters

Effect of sampling interval and operator duration are conveniently studied by considering the use of delay lines to approximate ideal filters, i.e., filters which

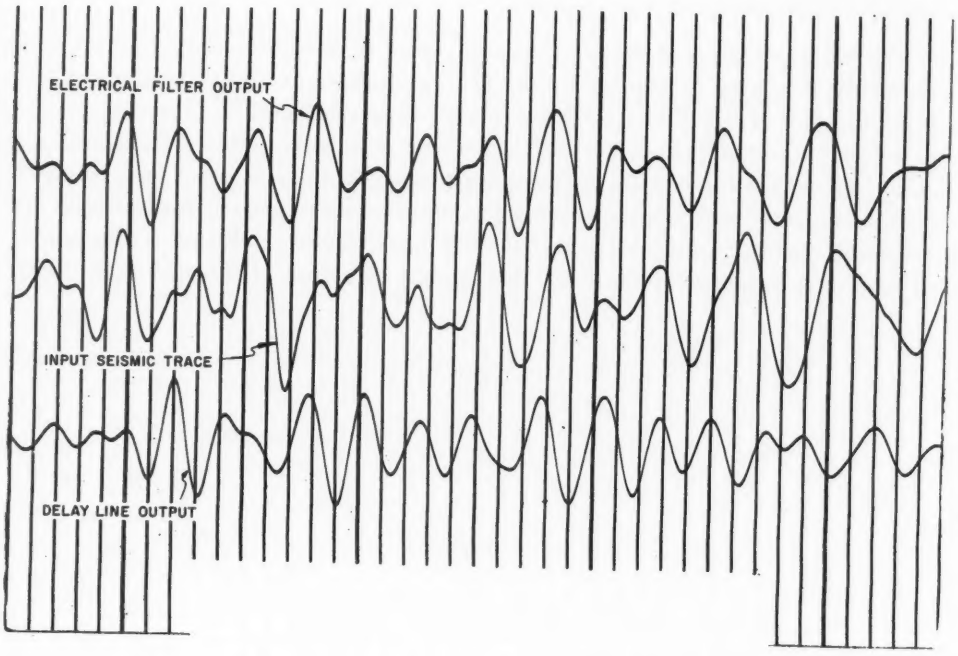

FIG. 6c. Comparison of seismic trace filtered by electrical filter and by 2-point delay line operator.

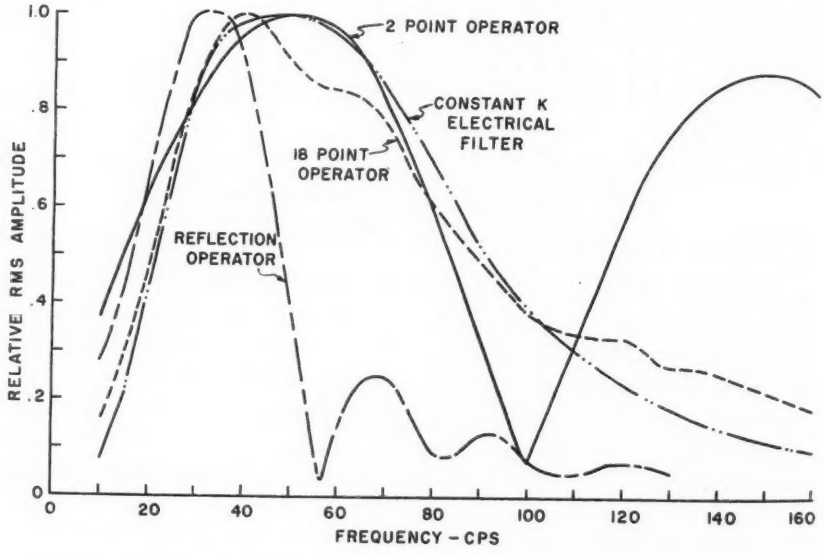

FIG. 7. Measured frequency spectra of operators used in Figures 6 and 14.

pass or reject all frequencies within their pass or stop bands, reject or pass all frequencies outside these bands, and produce zero phase shift. This problem may be approached by considering ideal low pass filters, from which other types may then be constructed. The response of an ideal low pass filter is shown in Figure 8. The weighting function corresponding to this filter is given by

$$K(t) = \frac{1}{2\pi}\int_{-\omega_0}^{\omega_0} e^{j\omega t}d\omega = \omega_0 \frac{\sin \omega_0 t}{\omega_0 t}. \tag{11}$$

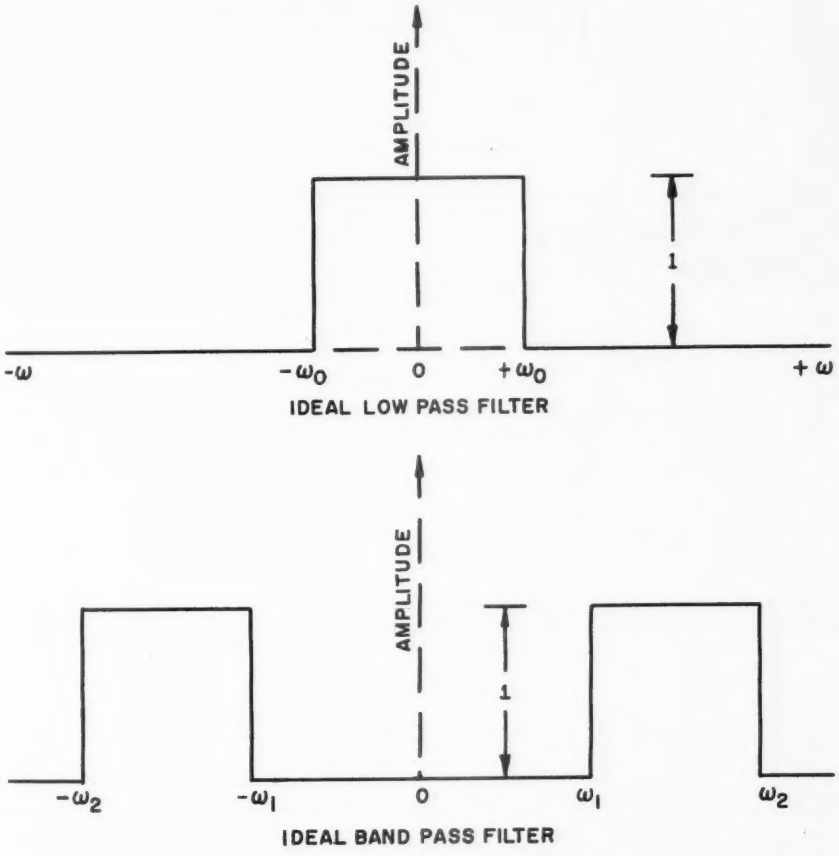

FIG. 8. Frequency responses of ideal filters.

The frequency transfer function is then specified by

$$K(\omega) = \omega_0 \int_{-\infty}^{\infty} \frac{\sin \omega_0 t}{\omega_0 t} \cdot e^{-j\omega t}dt. \tag{12}$$

Note that the weighting function of the ideal low pass filter is a symmetrical $(\sin x)/x$ function extending over the interval $-\infty < x < \infty$; thus such a filter

cannot be simulated by physical apparatus. We can, however, effectively obtain negative values of x by use of the delay line. The weighting function must be limited to a finite range $-t_0 \leqq t \leqq t_0$ determined by the length of our delay line; thus, we are interested in changes in the spectrum $K(\omega)$ due to variation of the limits of integration in the equation

$$\begin{aligned} K(\omega) &= \omega_0 \int_{-t_0}^{t_0} \frac{\sin \omega_0 t}{\omega_0 t} \cdot e^{-j\omega t} dt \\ &= \omega_0 \int_0^{t_0} \left[\frac{\sin (\omega_0 + \omega)t}{\omega_0 t} + \frac{\sin (\omega_0 - \omega)t}{\omega_0 t} \right] dt. \end{aligned} \tag{13}$$

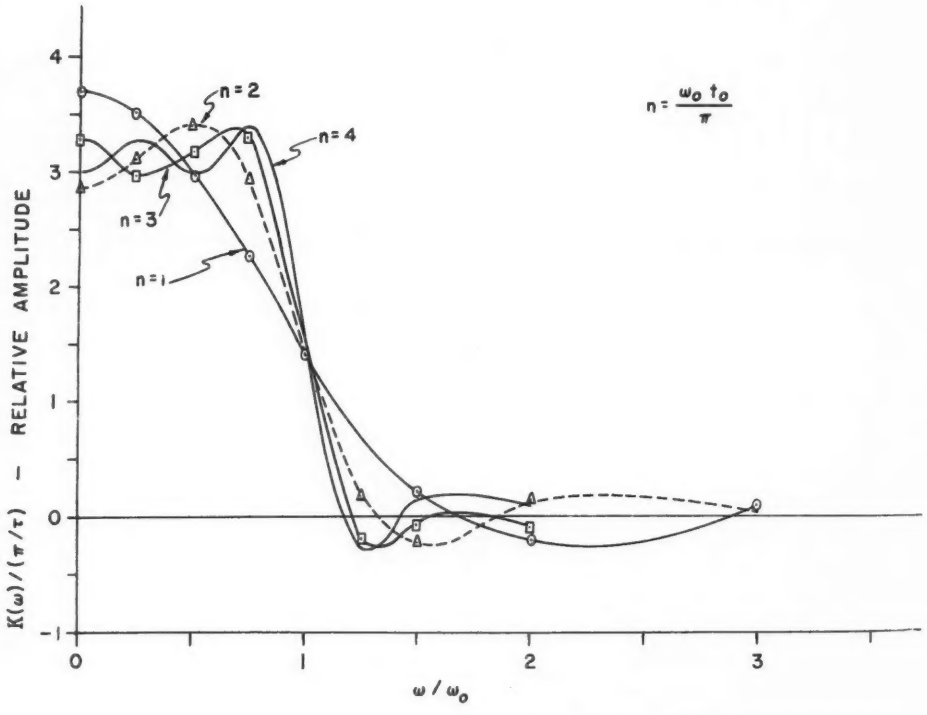

FIG. 9. Frequency response of continuous low pass filter operator for various operator durations.

If we let $\tau_1 = (\omega_0 + \omega)t$ and $\tau_2 = (\omega_0 - \omega)t$, we obtain from (13)

$$K(\omega) = \left[\int_0^{(\omega_0+\omega)t_0} \left(\frac{\sin \tau_1}{\tau_1} \right) d\tau_1 + \int_0^{(\omega_0-\omega)t_0} \left(\frac{\sin \tau_2}{\tau_2} \right) d\tau_2 \right]. \tag{14}$$

Now, if we let $t_0 = n\pi/\omega_0$, we obtain finally

$$K(\omega) = Si[n\pi(1 + \omega/\omega_0)] + Si[n\pi(1 - \omega/\omega_0)]. \tag{15}$$

The values of the *Si* functions for various arguments may be found in published tables, and thus the changes in spectrum as a function of limiting of time duration of the weighting function may be investigated for the continuous case. Results are shown graphically in Figure 9. Note that increase of operator duration produces more faithful modeling of the ideal filter.

The use of specific delay line apparatus to approximate ideal filters may be studied by returning to equation (5)

$$Z(t) = \sum_{K=1}^{M} a_K y(t - K\tau), \tag{5}$$

where now

$$a_K = \omega_0 \frac{\sin \omega_0 K\tau}{\omega_0 K}.$$

Since we are dealing with symmetric operators, it is convenient to change the operator interval to run from $-M'/2$ to $M'/2$ where $M' = M - 1$, so that "zero" is the center of the delay line, and the constant machine delay is $T/2$. The frequency transfer function of the delay line filter becomes

$$K(\omega) = \omega_0 \sum_{K=-M'/2}^{M'/2} \frac{\sin \omega_0 K\tau}{\omega_0 K\tau} e^{-j\omega K\tau}. \tag{16}$$

Since operator coefficients are symmetrical about zero, equation (16) can be written (for an odd number of coefficients, i.e., M' an even integer) as

$$K(\omega) = \omega_0 \left[1 + 2 \sum_{K=1}^{M'/2} \frac{\sin \omega_0 K\tau}{\omega_0 K\tau} \cos \omega K\tau \right]. \tag{17}$$

An equivalent formula for an even number of coefficients symmetrical about the center of the operator is

$$K(\omega) = 2\omega_0 \left[\sum_{K=1}^{M/2} \frac{\sin \omega_0 (2K - 1)\tau/2}{\omega_0 (2K - 1)\tau/2} \cos \omega (2K - 1)\tau/2 \right]. \tag{17.1}$$

Equation (17) can be used to study the effect of variations in cut-off frequency ω_0 for specified values of M and τ. This is most conveniently done by making the substitutions

$$\omega = c\omega_0 \quad \text{where } c \text{ is a constant}$$

$$\omega_0 = d \frac{\pi}{\tau} \quad \text{where } d \text{ is a constant} \leqq 1,$$

so that (17) becomes

$$\frac{K(\omega)}{(\pi/\tau)} = d \left[1 + 2 \sum_{K=1}^{M'/2} \frac{\sin \pi K d}{\pi K d} \cos (cK\pi d) \right]. \tag{18}$$

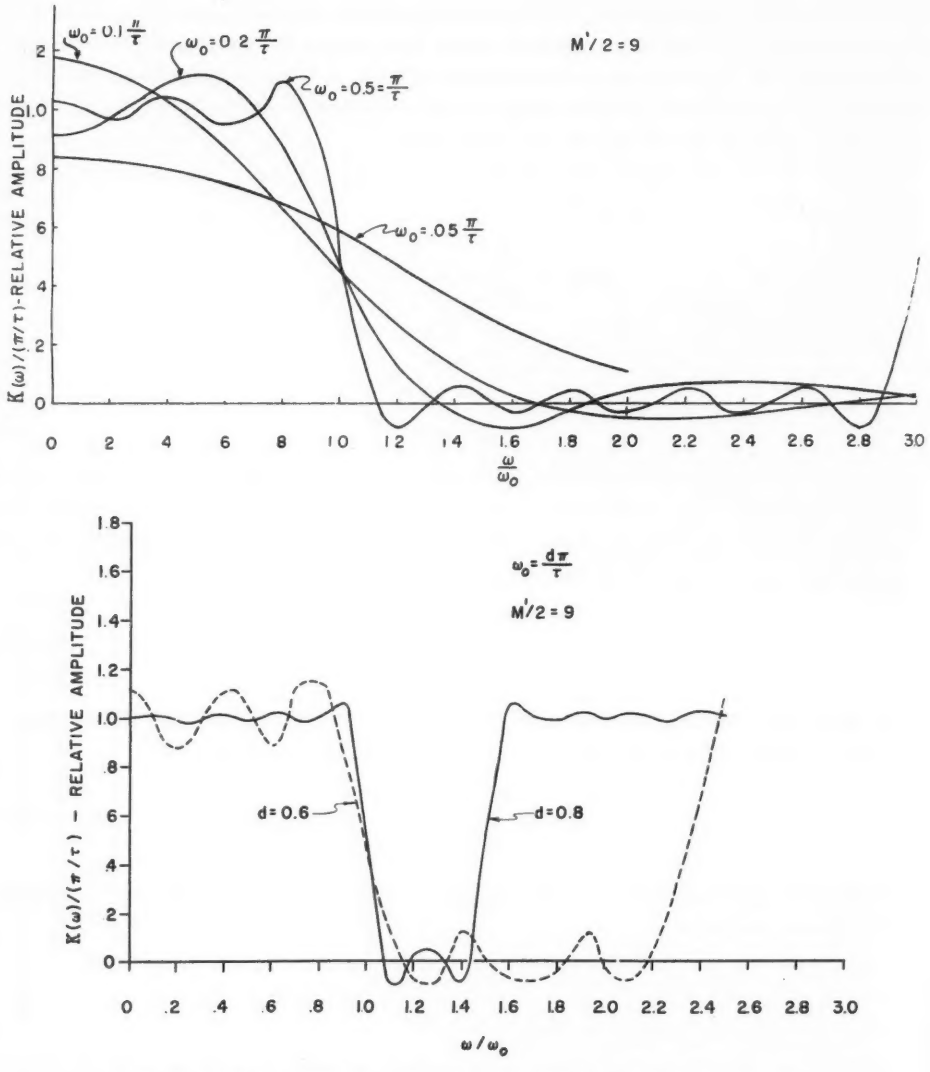
$\omega_0 = 0.1\frac{\pi}{\tau}$
$\omega_0 = 0.2\frac{\pi}{\tau}$
$\omega_0 = 0.5 = \frac{\pi}{\tau}$
$\omega_0 = .05\frac{\pi}{\tau}$
M'/2 = 9
K(ω)/(π/τ)-RELATIVE AMPLITUDE
0 2 4 6 8 10 12 14 1.6 1.8 2.0 2.2 2.4 2.6 2.8 30
$\frac{\omega}{\omega_0}$
$\omega_0 = \frac{d\pi}{\tau}$
M'/2 = 9
d = 0.6
d = 0.8
K(ω)/(π/τ) - RELATIVE AMPLITUDE
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0
ω/ω₀

FIG. 10. Predicted response of discrete low-pass filter operator, 19 samples.

Figures 10 and 11 show the frequency transfer function of a delay line filter as a function of $c=\omega/\omega_0$ for various values of d and for $M'/2=9$ and $M'/2=18$. Figure 12 compares actual and predicted frequency responses of the equipment of Figure 4 set up to approximate an ideal band pass filter. Figure 13 compares a seismic signal filtered by an electrical filter and by a delay line approximation to an ideal filter with comparable pass band.

The frequency spectrum of the delay line filter is repetitive with period $2\pi/\tau$ ($c=2/d$) due to the discrete sampling technique. Use of a particular value of τ

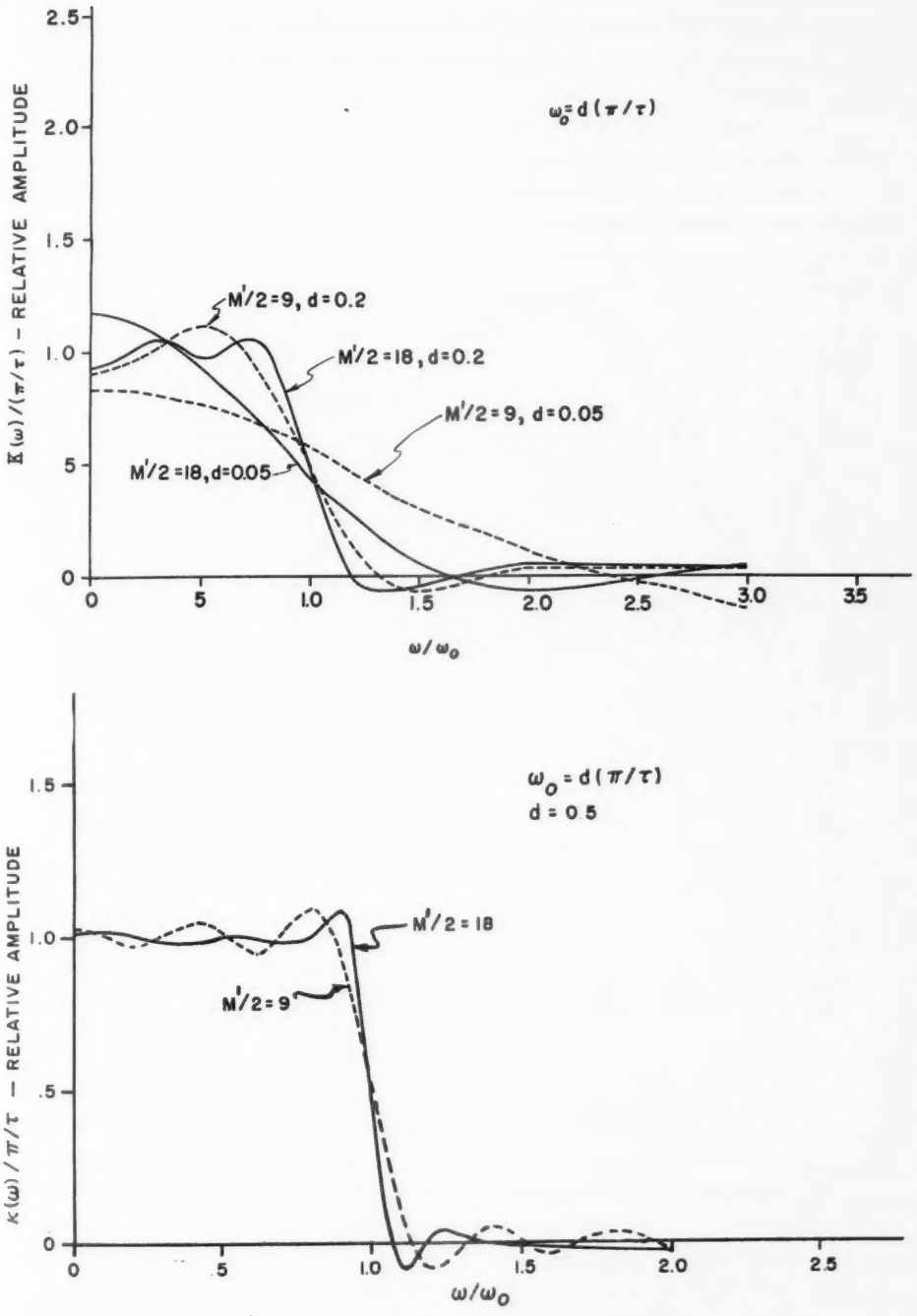

FIG. 11. Comparison of frequency response of discrete low-pass filter operator for 19 and 37 samples.

requires that all frequencies $|f| > 1/\tau$ should contribute negligible input power. Thus, in general, decrease of head spacing provides improved filter response at higher frequencies.

Also, as indicated above, increase of M (operator duration) improves resolution of adjacent frequencies, and thus provides sharper filtering; however, use of a very long operator is incompatible with the seismologist's objective of detecting arrival times of short transients.

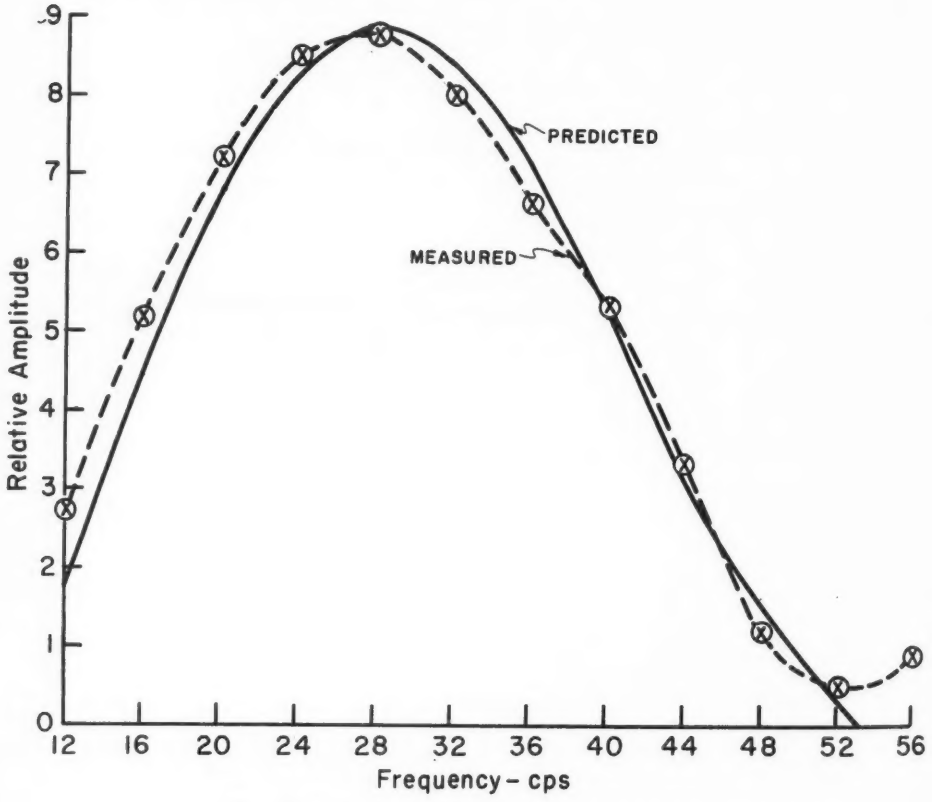

FIG. 12. Comparison of predicted and measured response of delay line filter operator approximating an ideal 20–40 cps band pass filter.

The above discussion covered ideal low pass filters; however, it is clear that operators for ideal band pass or band stop filters can be obtained by superimposing low pass weighting functions or directly from the Fourier transform. Both low pass and band pass approximations introduce no phase shift. This can be seen by inspection of equation (17) which shows no imaginary term in the frequency transfer function $K(\omega)$. This is, of course, a result of the symmetry of the operator coefficients a_K.

An advantage of the delay line filter is that phase and amplitude characteristics can be adjusted somewhat independently. As an example, all symmetrical operators produce zero phase shift; however, a wide variety of amplitude characteristics can be obtained.

Cross-Correlation

The delay line filter can be used for cross-correlation against expected waveforms (Jones and Morrison, 1954) since the weighting function in this application is simply the inverse expected signal wavelet. Figure 14 illustrates use of the

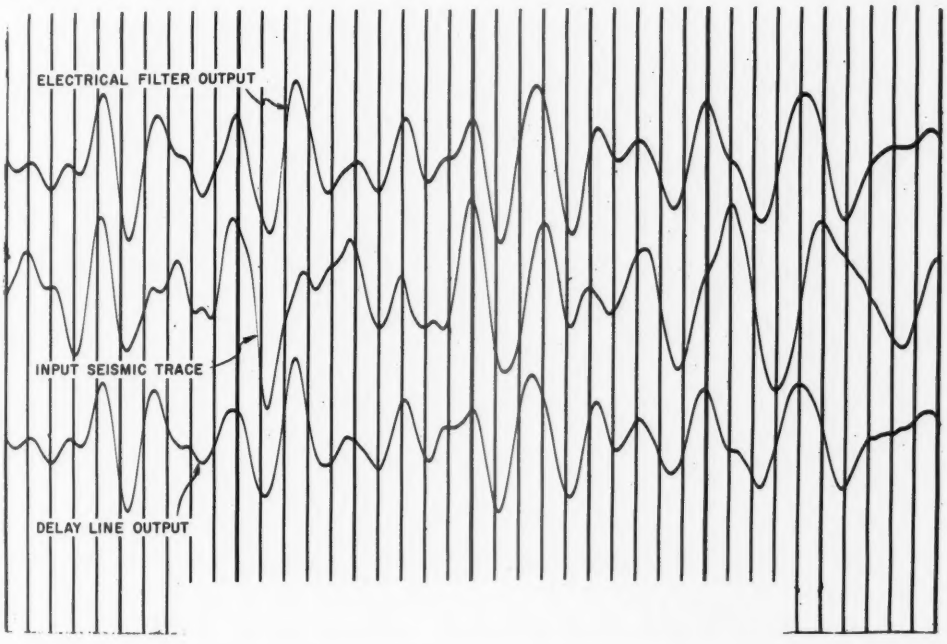

FIG. 13. Comparison of seismic trace filtered by electrical filter and by symmetrical operator with similar amplitude vs. frequency characteristics.

delay line as a cross-correlator. The expected signal of Figure 14 was chosen from the input signal of Figure 6b, so that results of cross-correlation filtering and conventional filtering could be compared. In setting up the apparatus of Figure 3 for this application, the expected wavelet is introduced with its beginning at the pickup head adjacent to the erasing magnet since the time coordinate of the input increases in a direction opposite to the direction of movement of the input past the pickup heads.

Zero-phase-shift Filters

As outlined above, zero-phase-shift filters may be obtained by use of symmetrical filter operators. In addition, zero-phase-shift linear filters of arbitrary ampli-

tude spectrum may be approximated using the delay line in the following very simple manner:

1. Play through the delay line using the desired time function a_K as the filter operator; i.e., cross-correlate against the impulse response wavelet,

2. Replay through the delay line using the *inverse* impulse response wavelet as the operator, e.g., by reversing the order of potentiometer settings.

The effective filter obtained by this procedure has zero phase shift and an amplitude spectrum which is the square of the amplitude spectrum of the filter operator used.

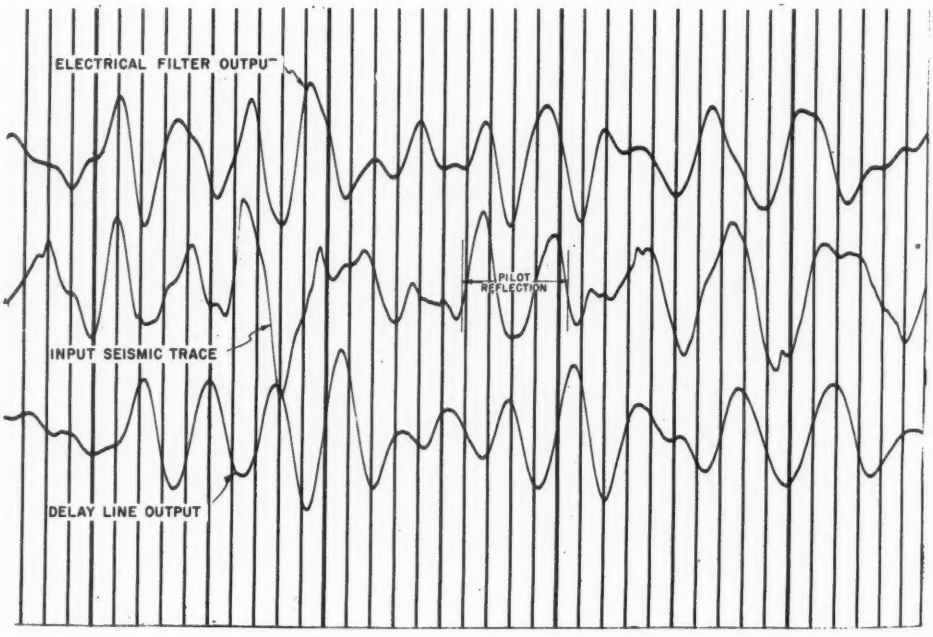

FIG. 14. Comparison of seismic trace filtered by electrical filter and by pilot reflection operator.

Multiple Seismometer and Source Arrays

The linear operator theory outlined above may be applied to multiple seismometer (or source) arrays (MIT, 1954). To illustrate this simply, we consider a linear array of evenly spaced seismometers and assume steady state plane waves. The filtered output of the array at time t is then given by

$$Z(t) = \sum_{K=1}^{M} a_K y(t - K \cdot \Delta X \cdot \sin \theta / V) \tag{19}$$

where

M = number of seismometers,

ΔX = seismometer spacing,
θ = angle between wavefront normal and the vertical,
V = plane wave velocity (assumed constant over the total spread distance).
The output spectrum is

$$Z(\omega) = K(\omega) \cdot Y(\omega),$$

where $Y(\omega)$ is the input spectrum and $K(\omega)$ is the array transfer function given by

$$K(\omega) = \sum_{K=1}^{M} a_K e^{-j\omega K \cdot \Delta X \cdot \sin\theta/V}. \tag{20}$$

In the common situation of equally weighted seismometer outputs, the a_K's all equal unity and (20) becomes

$$K(\omega) = \sum_{K=1}^{M} e^{-j\omega K \cdot \Delta X \cdot \sin\theta/V}. \tag{21}$$

The array amplitude spectrum is given by

$$|K(\omega)| = \frac{\sin [M\omega \cdot \Delta X \cdot \sin \theta/2V]}{\sin [\omega \Delta X \cdot \sin \theta/2V]},$$

and the phase shift (with respect to the first detector, $K = 1$) by

$$\text{angle } K(\omega) = (M - 1)\omega \cdot \Delta X \sin \theta/2V.$$

Optimized Linear Operators

A wide variety of criteria may be applied in an effort to "optimize" the operator coefficients a_K in order to achieve a particular desired filter output, e.g., the least mean square method of MIT (Wadsworth et al., 1953). Filtering by such operators can be modeled by delay line apparatus, rather than by use of digital computers as has been done by MIT. The latter method requires tedious analog-to-digital conversion by manual or semi-automatic means when conventional records are employed. Electrical signals played back from magnetic recordings can, however, be sampled, coded, and recorded in suitable form for digital computer entry, although at present the cost of necessary equipment is very high. Once the data have been satisfactorily converted, a wide variety of filtering can be accomplished computationally by linear or non-linear operator techniques.

NON-LINEAR FILTERS

Use of delay line filters is not restricted to linear operators, and a wide class of non-linear filters also may be modeled. Following Zadeh (1953) we may relate the input and output of a simple class of non-linear filters by the following integral expression

$$Z(t) = \int_0^T F[y(t-\tau), \tau]d\tau, \tag{22}$$

where $F[y(t-\tau), \tau]d\tau$ is an arbitrary real function of the input $y(t-\tau)$. A discrete formula for the delay line approximation to (22) is

$$Z(t) = \sum_{K=1}^{M} F_K[y(t - K\tau)], \tag{23}$$

where the F_K's are arbitrary real functions. The linear filter (equation (5) is a special case of (23). To model equation (23) with apparatus such as is shown in Figure 3, one must add appropriate function generators after the output of each pickup head.

Wider classes of non-linear filters than that described by equation (22) are possible and also may be described by summation equations, e.g.,

$$Z(t) = \sum_{K,L,M,\cdots X} F_{K,L,M,\cdots X}[y(t - K\tau), y(t - L\tau), \cdots, y(t - X\tau)];$$

$$K, L, M, \cdots X = o(1)n. \tag{24}$$

An m-dimensional delay line filter is required to simulate (24) with compositing of the outputs of appropriate sampling points on each of m individual delay channels (alternatively one could employ a single delay channel with proper interconnection of sampling points).

Drenick (1954) gives an example of an optimum non-linear sampling filter which may be simulated by a single delay line channel with multiply interconnected sampling points and shows that, for a specific problem, such a filter is superior to the optimum linear filter. This conclusion seems valid in general since the class of linear filters can be shown to be a special case of Zadeh's m-dimensional class of non-linear filters.

As a very simple example of a non-linear filter, consider the case where each potentiometer in the apparatus of Figure 3 is replaced by a squaring device. The filter input-output relationship is then given by

$$Z(t) = \sum_{K=1}^{M} [y(t - K\tau)]^2 \tag{25}$$

and is a presentation of computed running mean power of the input. Such a presentation has been found very useful in problems of detection of signals contaminated by Gaussian noise. In such problems, the mean power of the noise is nearly constant when a sufficiently large value of M is employed in equation (25) and the arrival of a signal produces readily detectable incremental changes in mean power.

REMARKS

Magnetic recording delay line instrumentation provides a very flexible means for simulating a wide variety of both linear and non-linear filtering operations.

A single-channel delay line programmed for automatic sequential playback permits filtering of an N-trace magnetic record of T seconds duration in NT seconds, e.g., 2 minutes for a 24-trace, 5-second record. Use of n channels reduces the total playback time to (NT/n) seconds. Multi-channel delay line apparatus can be used to model m-dimensional linear or non-linear filtering operations.

Use of linear delay line filtering apparatus permits the operator to simulate zero phase shift filters with arbitrary amplitude function. Also, he may approximate an inverse to any linear (not necessarily minimum phase) filter. The theory used to study linear delay line filtering can be applied to multiple seismometer and source arrays. Thus, the relationship between array pattern and array transfer function can be studied by Fourier transform methods.

Finally, magnetic recording delay lines have a number of possible applications in seismic data processing other than filtering, e.g., to introduce time corrections in raw magnetically-recorded data and in apparatus for compositing seismometer group outputs with variable relative delay to emphasize signals with particular angles of incidence.

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GEOPHYSICS, VOL. XX, NO. 4 (OCTOBER, 1955), PP. 766–773, 3 FIGS.

AN AMPLITUDE STUDY ON A SEISMIC MODEL*

C. S. CLAY†‡ AND HALCYON McNEIL†

ABSTRACT

The measured amplitudes of two seismic events which have traveled through a two layer seismic model are compared with the amplitudes calculated from plane wave reflection and transmission theory.

The relative amplitudes of the events, one a dilatational-dilatational and the other a dilatational-to-shear conversion event, are found to be in agreement with calculations based on reflection theory for plane waves, after correction for $1/r^2$ divergence.

INTRODUCTION

It has become possible with the development of seismic models to attack certain seismic problems in the laboratory. In some cases, these experiments can be regarded not only as model studies but also as actual seismic experiments on a small scale. Thus we can test the applicability of the present elastic wave theory to seismic problems. Evans et al. (1954) have made a study of the events transmitted along a thin plate and have shown good agreement with the normal-mode theory as applied to the thin plate by Tolstoy and Usdin (1953). Similarly, Press and Oliver (1955) have demonstrated in the laboratory many properties of the air-coupled flexural wave.

An attractive feature of a seismic model is that a single repeating source and a single detector may be used for making comparisons of the amplitudes of seismic events. The seismic model studies of Levin and Hibbard (1955) have shown that the dilatational to shear conversion events are very prominent. For this reason, it seemed desirable to make a quantitative amplitude study of a dilatational event and a dilatational-to-shear conversion event and to compare the experimental results with amplitudes calculated from theory. Since it was not practical to follow a more rigorous analysis of the problem such as was made by Cagniard (1939), comparison of experimental data with the transmission amplitudes calculated from plane wave theory was made. Actually the problem to be solved was the case of spherically diverging waves and, as an approximation, the plane wave amplitudes were corrected by a $1/r^2$ divergence factor.

Levin and Hibbard have shown that the measurement of reflection amplitudes would be very difficult on this model because of the interference between reflections and other events, such as ground roll. However, the first arriving transmitted events are relatively free from interferences, so the amplitude study has been made on these events. The dilatational event is the dilatational wave through

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cement and dilatational wave through marble, P_1P_2. The conversion event is the dilatational wave through cement converted at the interface to a shear wave (SV) through marble, P_1S_2.

EXPERIMENTAL AMPLITUDES

The amplitude measurements were made with the two-layer seismic model used by Levin and Hibbard.[1] A spark gap was used as the seismic source and a barium titanate ceramic was used for the detector.[2] It seemed desirable to make

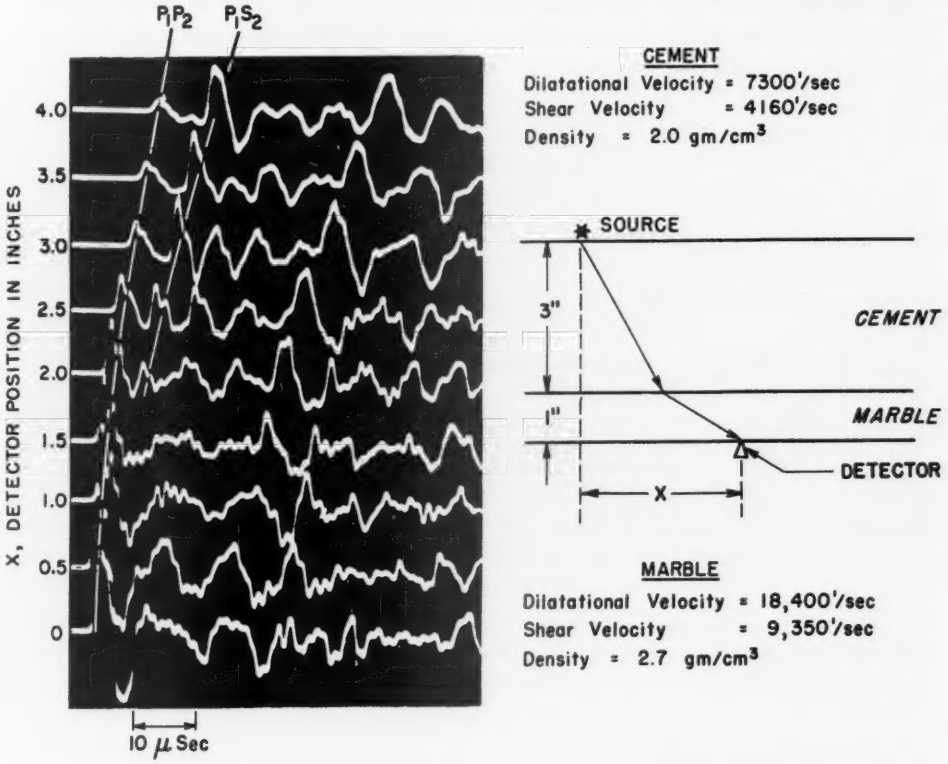

FIG. 1. Transmission through two layer seismic model (with constant gain).

the amplitude study with the transient from a spark so as to simulate the phase distortion from a shot that might be expected in seismic events for incident

[1] The model consisted of a layer of 3" Sauereisen #31 cement over a 1" layer of marble. The model had an areal extent of approximately 5'×7'. It was possible to place source and detector on either the top (cement) or bottom (marble) so as to make reflection and transmission studies.

[2] The spark gap was the open end of a coaxial line after Kaufman and Roever (1951). The outer conductor of the line was thin-wall $\frac{1}{8}$-inch-diameter stainless steel tubing; the inner conductor, .045 inch steel wire; and the insulation, plastic radio spaghetti. A rotary switch was used to place a 2-μf capacitor charged to 800 volts across the spark gap. The spark repetition frequency was about 4 pulses per second.

angles greater than critical. Distortion of the pulse was discussed theoretically by Fisher (1948). Arons and Yennie (1950) have done experiments in shallow water in which phase distortion of oblique reflections was observed.

The detector, the same as that used by Levin and Hibbard, was a barium titanate ceramic which worked into a cathode follower with very high input impedance. The size of the detector was kept as small as practical, approximately $\frac{1}{8}$-inch square, and the thickness of the ceramic was 0.1 inch. Since barium titanate ceramics seem to be largely sensitive to vertical motion with low sensitivity to horizontal motion, the amplitude data were not corrected for detector response. The amplifying system and oscilloscope were the same as those used by Levin and Hibbard, with flat response from 10 kc to 5 mc.

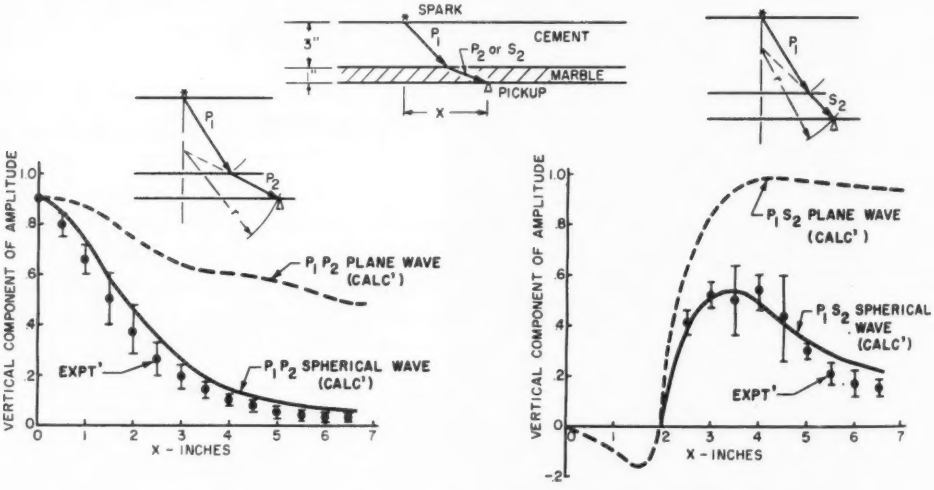

FIG. 2. Comparison of the experimental amplitudes and the vertical components of the theoretical amplitudes for the transmitted events. The theoretical plane wave amplitudes are shown uncorrected and with r^{-2} correction for spherical spreading. r is the apparent radius of curvature of the wave front.

A model seismogram, taken with the spark, is shown on Figure 1. The seismogram was made by taking a series of multiple exposures, one exposure for each detector position. The film in the camera was moved for each exposure, making it possible to leave the oscilloscope trace in the same position and to use the same field of view of the camera lens. Each trace of the seismogram was made with an exposure of about 5 sec with the spark repeating 4 times per second.

The transmission events P_1P_2 and P_1S_2, which were chosen for the amplitude study, have been identified on the seismogram shown in Figure 1. The first event, dilatational through cement-dilatational through marble (P_1P_2), is transmitted for incident angles of the dilatational wave P_1 in the cement which are less than the critical angle. However, at detector positions less than two inches from the source (corresponding to a less-than-critical angle of incidence for the P_1P_2

event), the converted shear wave P_1S_2 was not identifiable. For angles of incidence greater than critical or detector positions farther than 2 inches from the source, the dilatational wave that was converted to shear at the cement-marble interface has been identified on Fig. 1 as the P_1S_2 event.

The experimental amplitudes for each event are shown on Figure 2. The amplitudes were measured on enlarged photographs similar to the seismogram on Figure 1. In addition to the detector which was moved, another detector was held stationary during the recording of a profile as a monitor of the source amplitude. Inasmuch as the cement layer contained a large number of small air bubbles, the spark and detector were moved to different positions on the model in order to obtain a better average value for the transmission amplitudes and to reduce the effect of random local inhomogeneities in the model. Each data point on Figure 2 represents the average value of the amplitudes from three profiles and the spread that is shown is the standard deviation of the values. All amplitude data were normalized to a transmitted dilatational amplitude of 0.91 at zero detector distance so that they would agree, at that position, with the theoretical transmission amplitudes for plane waves.

THEORETICAL AMPLITUDES

The plane-wave amplitude calculations were made by the Zoeppritz equations described by Macelwane and Sohon (1936, p. 147–178). The actual calculation was carried out in steps as follows: A unit dilatational plane wave in the cement was assumed to strike the cement-marble interface at a given angle and the components reflected from and refracted into the marble were computed. The amplitudes of the incident wave, the reflected dilatational, reflected shear conversion, refracted dilatational, and refracted shear conversion waves were fitted together mathematically at the interface so as to satisfy the boundary conditions. Since there are four unknown amplitudes, it was necessary to solve four simultaneous equations. This process was repeated for each angle of incidence to obtain the amplitudes of the reflected and refracted waves. The direction of travel or angle of incidence of each wave was obtained from Snell's law.

The calculation of the vertical component at the free surface of the cement or marble was a similar but less complex problem in two unknowns. In this case, the incident dilatational wave was reflected both as a dilatational and as a shear wave, as was also the incident shear wave. The boundary condition of zero stress on the free surface, together with the use of Snell's law, gave the amplitude of the reflected events. The vertical component of displacement, observed on the surface, was found by calculating the vertical component of the sum of the incident and reflected waves. For example, the dilatational wave at vertical incidence was reflected with the same amplitude but opposite phase. Thus, the amplitude of the displacement at the free surface was twice that of the incident wave. The assumptions made were first, that the plane waves are of single frequency; second, that absorption may be neglected; and third, that there is no body motion

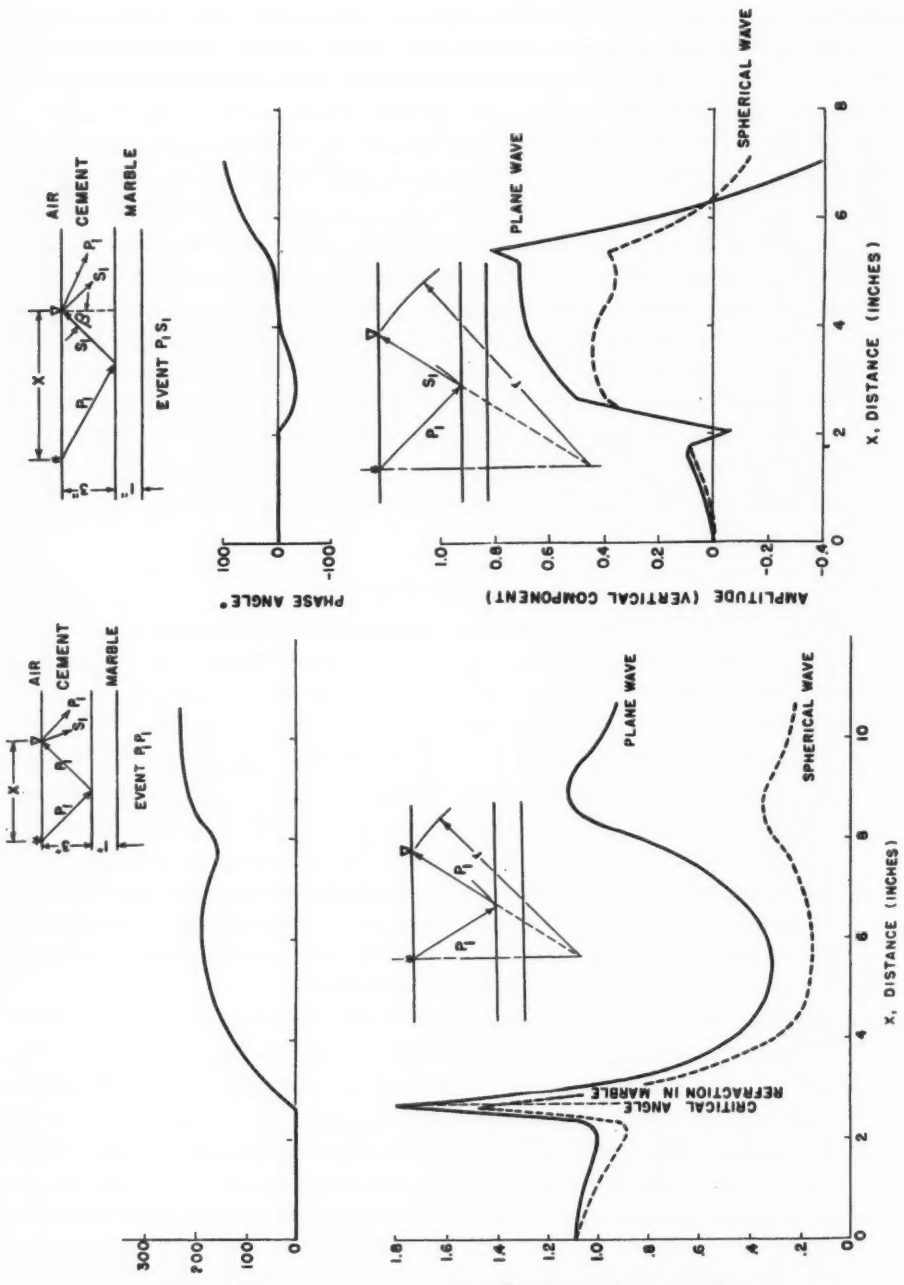

FIG. 3. Theoretical vertical components and phase of reflected events. The plane wave amplitudes and the same with r^{-2} correction for spherical spreading are shown. r is the apparent radius of curvature of the wave front.

of the whole layer. The relative amplitudes of the vertical displacements for the plane-wave calculations are shown in Figures 2 and 3. The null at about the 2-inch position for the dilatational-shear transmitted event corresponds to the dilatational-reflection critical angle.

The plane-wave amplitudes were approximately corrected for spherical spreading in the following manner. The amplitudes were assumed to decay as a function of the radius of curvature of the wave front. It can be seen that the curvature of the wave front changed upon passing from the cement into the marble and that the position of the apparent center of curvature was not constant except for the dilatational-reflection case. The refraction of spherical waves by a plane surface has been treated as an optical problem by Robertson (1941) in section 20 of his text. Figure 3 shows the wave-front curvature for both the P_1P_1 and the P_1S_1 reflections.

The decay function of the amplitudes was determined experimentally. The ratios of the experimental amplitudes to the corresponding plane wave amplitudes were fitted by least squares to the functions Ae^{-ar}/r and Be^{-br}/r^2 in order to better determine the form of the expression for amplitude decrease. The sum of residuals squared was calculated for each case. The average of the residuals squared for the expression involving r^2 was about one third of the average for the inverse r expression. For this reason, reciprocal r^2 was chosen to modify the plane wave amplitudes for spherical divergence.[3]

Mencher (1952, 1953) and Dix (1954, 1955) have shown that the displacement potential function due to a step function in a displacement-type point source yields, as the solution of the wave equation, an amplitude decreasing as the inverse square of the distance and a derivative which decreases inversely as the distance. Thus, near the source the displacement decreases as r^{-2} and at large distance the form of the disturbance is changed and its displacement decreases as r^{-1}. The experimental amplitudes were best fitted by r^{-2}, which indicates that the model experiments were made under near-source conditions.

If the transmission amplitudes with spherical approximation are compared with the corresponding plane-wave amplitudes, as shown in Figure 2, it can be seen that the amplitude of both P_1P_2 and the converted shear P_1S_2, are considerably reduced at distances greater than 3 inches. In a similar manner the reflected events are also altered. If the reflection amplitudes with spherical wave front corrections are compared with the corresponding plane wave amplitudes, as shown in Figure 3, it can be seen that the dilatational reflection maximum at about 8 inches is very much smaller and that the reflected shear amplitude is also reduced. The effect of directivity of the source has not been included in these calculations.

The directivity of the source was similar to the directivity given by Sezawa and Kanai (1936) for a piston-type source. The theoretical amplitude of the

[3] The ratios of experimental to theoretical amplitudes were also considered as functions of travel time. The results of this indicated that the decay was t^{-6} for the P_1P_2 event and $t^{-3.3}$ for the P_1S_2 event. These results were different from the $t^{-2.5}$ relation obtained by Ricker (1953) in a single medium.

P_1P_2 event is almost unchanged by correction for the source directivity. The departure angle of P_1 is less than 24° from the normal to the surface and the correction is less than 2%. The theoretical amplitude of the P_1S_2 event is changed at large x. At $x = 5''$, the departure angle of P_1 is about 45° and the correction factor for source directivity is 0.6. The source correction would reduce the theoretical values still more at larger x. The agreement of the theoretical and experimental amplitudes is improved by correction for the source directivity.

CONCLUSION

For the transmission case, the agreement between approximate theoretical calculations and the experimental measurements is quite good. The theoretical work was done under the assumption that the source of dilatational waves was uniform in all directions. The experimental source was directive vertically and this may account for the reduced experimental amplitude at large distances. The amplitudes of the dilatational event at zero detector position, and the shear wave at 3 inches, as determined experimentally were in good agreement with the theoretical amplitudes at these distances and this comparison should give more confidence in the use of such theoretical approximations. Of course, approximate calculations such as these cannot apply at the critical angles and one must use more exact treatments, such as those of Cagniard (1939) and Heelan (1953), which consider the coupled nature of the vector and scalar displacement potential functions.

The reflection amplitudes have not been studied in these experiments. It is believed, however, that the theoretical amplitudes shown on Figure 3 would be observed if it were possible to obtain the reflections free of interferences, because the incident, reflected, and transmitted events are connected by boundary conditions at the interface. Thus, the procedure of calculating the plane-wave reflected and transmitted amplitudes and then making an approximate correction for spherical divergence of the wave front may be an adequate treatment of this problem.

ACKNOWLEDGMENT

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GEOPHYSICS, VOL. XX, NO. 4 (OCTOBER, 1955), PP. 774–779, 2 FIGS.

VELOCITY ANISOTROPY IN STRATIFIED MEDIA*

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ABSTRACT

The phenomenon of velocity anisotropy in stratified rocks has been observed in surface outcrops by McCollum (1932), Weatherby (1934), Ricker (1953), White and Sengbush (1953), and their associates. In 1944, 1948, and 1953 Shell Oil Company measured oblique times from shots spaced at large distances from a well to a seismometer in the well and found evidence of velocity anisotropy. Cholet and Richards (1954) also observed this phenomenon in well-velocity surveys at Berriane (North Sahara).

An anisotropy factor A which is defined as the ratio of the velocity along the layers to the velocity perpendicular to the layers, has been computed from oblique-time and well-survey data. The factor A varies between 1.1 and 1.4 for the data collected in this report.

At present, information on velocity anisotropy is limited and it is therefore suggested that oblique time measurements be made along with vertical velocity surveys whenever possible.

INTRODUCTION

The conventional methods of computing seismic data assume velocity isotropy. For most computations this assumption is probably accurate enough; however, in some instances velocity anisotropy is important (Rice, 1949).

The phenomenon of velocity anisotropy has been observed in surface formations by McCollum (1932), Weatherby (1934), Ricker (1953), White and Sengbush (1953), and their associates. In 1944, 1948, and 1953 Shell Oil Company measured oblique times from shots spaced at large distances from a well to a seismometer in the well. The observed times could be explained only by velocity anisotropy. In this paper a summary of these data is given and other published data on velocity anisotropy in stratified rocks are reviewed.

A QUANTITATIVE MEASURE OF VELOCITY ANISOTROPY

For the purpose of expressing the degree of velocity anisotropy, an anisotropy factor, denoted by the symbol A and defined as the ratio of the velocity along the layers to the velocity perpendicular to the layers, is used in this paper. For horizontal layers this factor is defined as the ratio of the effective horizontal velocity to the average vertical velocity for the interval being studied.

The value of A for data observed in surface formations was computed by taking the ratio of the velocity along the layers to the velocity perpendicular to the layers. The value of A for the oblique time measurements from shots to a seismometer in a well (Figure 1) was computed by substituting the known values of T, X, Z, and V in the equation

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‡ Shell Development Company, Houston, Texas.

$$T^2 = \frac{X^2}{A^2V^2} + \frac{Z^2}{V^2},$$

where A is the anisotropy factor as defined above, X and Z are the conventional distance and depth coordinates of points on the wave surface at time T, and V is the average vertical velocity for the depth Z.

The A factor for various areas in the United States and Canada is shown in Table I. The factor A lies between 1.10 and 1.19 for data observed by Shell in well surveys. Recently, J. Cholet et al. (1954), determined an anisotropy coefficient

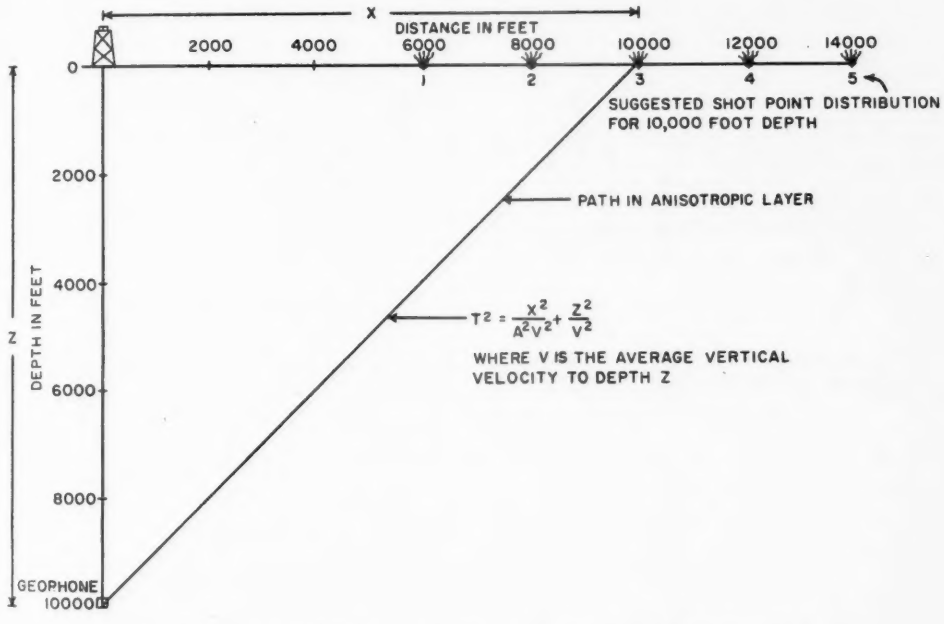

FIG. 1. Geometry of well survey with proposed shot point distribution for determination of velocity anisotropy.

of about 1.09 from measurements down to 1,250 meters in Berriane district in Northern Sahara. The factor A for the values observed along the surface outcrops of layers dipping close to 90° varied between 1.3 and 1.4. Comparable observations of the A factor for horizontal subsurface layers could be made in gently dipping areas by measuring, in addition to the vertical velocities, the horizontal velocity between two wells about one-quarter mile apart.

In 1949 Postma, Riznichenko, and Stoneley independently examined the case of "transversely isotropic" media. Distinctly but finely stratified formations would answer this description. The line perpendicular to the strata is an axis of symmetry. An example would be a formation consisting of alternating bands of limestone and shale or sand and shale, the thickness of the bands being small

TABLE I

DATE	NO. OF OBSERVATIONS	DEPTH OF SEISMOMETER IN FEET	SHOOTING DISTANCE IN FEET	VERTICAL VELOCITY FPS	"A" FACTOR	FORMATION	LOCATION	SOURCE
1932	–	SURFACE	–	–	1.4	LORRAINE SHALE	CANADA	McCOLLUM, ET AL
1934	–	SURFACE	–	–	1.3	ARBUCKLE LIMESTONE	OKLAHOMA	WEATHERBY, ET AL
1944	4	7216	5300 & 10550	12100	1.14	PERMIAN & PENN	SHELL TANKERSLY NO. 1 IRION CO., TEXAS	VAN MELLE, ET AL
1948	2	8160	5635 & 8300	11380	1.13	PERMIAN & PENN	SHELL KINCAID NO. 1 CROCKETT CO., TEXAS	VAN MELLE, ET AL
1953	4	7913	6000 to 10000	11400	1.19	PERMIAN & PENN	SHELL ALDWELL NO. 1 SUTTON CO., TEXAS	UHRIG
1953	8	7764	5265 to 10837	12130	1.10	LOWER CRET. & PENN	HUMPHREY-OSBORNE NO. 1 HILL CO., TEXAS	ROBERTSON
1953	–	SURFACE	–	–	1.18	PIERRE SHALE	LIMON, COLORADO	RICKER
	–	SURFACE	–	–	1.14	PIERRE SHALE	LAST CHANCE, COLORADO	RICKER
1953	–	SURFACE	–	–	1.17	AUSTIN CHALK	DALLAS, TEXAS	WHITE, ET AL
	–	SURFACE	–	–	1.33	EAGLE FORD SHALE	DALLAS, TEXAS	WHITE, ET AL

compared to the wave length dominant in the signal. The investigations showed that under such conditions plane compressional waves must travel with different velocities in different directions with respect to the line of symmetry. Postma (1955) computed the effective horizontal and vertical longitudinal velocities for two cases of a medium having thin bands of high and low velocity layers. The computed A factors for these cases were close to the values found from oblique time measurements in well surveys by Shell in West Texas.

It appears that apparent anisotropy in stratified rocks might be caused first by fine stratification (transversely isotropic media); secondly, by homogeneous

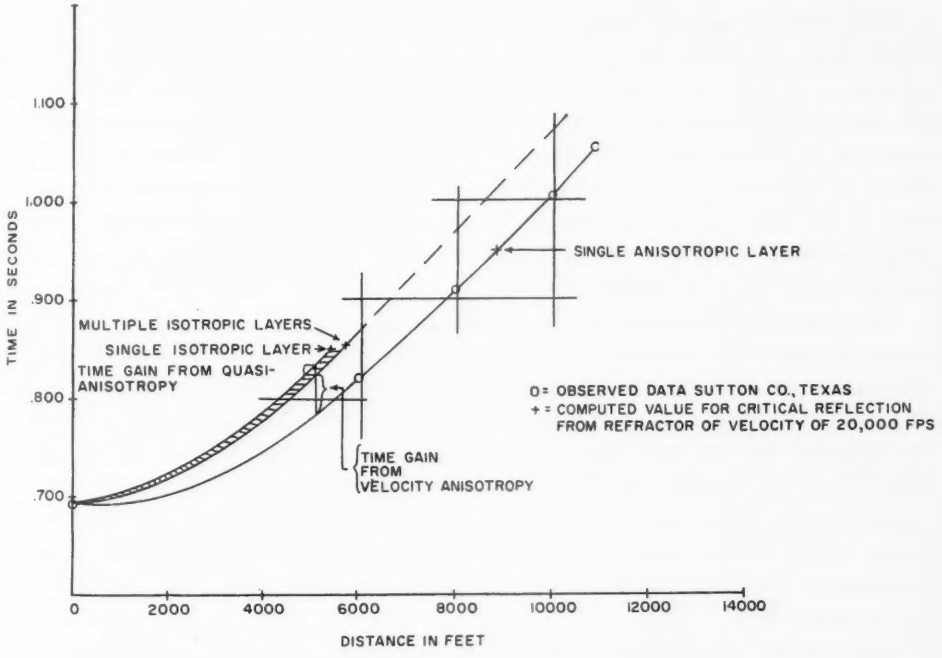

FIG. 2. Time-distance curves.

anisotropy in each homogeneous rock member; thirdly, by quasi-anisotropy associated with stratification not necessarily fine compared to the wave length. Quasi-anisotropy follows from Fermat's principle, which requires that the average velocity for an oblique path through a sequence of parallel isotropic layers of different speeds be higher than the average velocity for a path traversing the same layers vertically. The amount of time saved on the actual refraction path over the time that would be spent on the straight-line path is a measure of the quasi-anisotropy; and it is therefore, like the other kinds of anisotropy, a function of the angle between the incident ray and the layers.

In Figure 2, the calculated minimum-time versus distance curves for a single isotropic layer of average speed and for several isotropic component layers are

shown, as well as the observed oblique times. The velocities used in the computations were based on well survey data from Sutton County, Texas. It is evident that the time-distance values computed under the assumption of quasi-anisotropy account only for a small part of the time gain observed on the oblique paths over the times computed for the straight line path of average velocity. All of the observed time gain can, however, be explained by velocity anisotropy. The travel times alone do not allow a distinction between transversely isotropic (finely layered) and homogeneously anisotropic media.

SUMMARY AND SUGGESTIONS

The effect of velocity anisotropy in stratified media has been observed in Texas, Oklahoma, Canada, and Colorado. The anisotropy factor A for relatively homogeneous rock members of surface outcrops varies between 1.17 and 1.40, and for 7,000 to 8,000 feet of clastic and carbonate sediments below the surface varies between 1.10 and 1.19. Velocity anisotropy is probably the result of three effects: homogeneous anistropy in individual rock layers; transversely isotropic rock layers; and, for the oblique paths, quasi-anisotropy caused by time differences between straight line and minimum-time paths assuming a sequence of isotropic formations of different speeds.

The available data suggest that velocity anisotropy is large enough to be a factor of importance in seismic computations. At the present time, the amount of information is limited; it is suggested that measurements of velocity anisotropy be made when vertical velocity surveys are conducted. This can be done simply by recording the oblique times to a seismometer in a well from shots spaced at distances comparable to the depth of the seismometer in the well. Shotpoints at 2,000-foot intervals on both sides of the well up to a distance equal to the depth in the well should be sufficient. Such a program may be restricted by limiting it to distances from the well about equal to the depth of the most important reflecting or refracting levels.

The writers are indebted to Mr. M. H. McKinsey, who took an active part in the early interpretations, and to Mr. G. Robertson, who supervised the field work associated with the later well surveys. Appreciation is expressed also for helpful suggestions by Drs. Hafner and Postma, and by members of the Geophysical Staff of Shell's Midland Area.

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GEOPHYSICS, VOL. XX, NO. 4 (OCTOBER, 1955), PP. 780–806, 13 FIGS.

WAVE PROPAGATION IN A STRATIFIED MEDIUM*

G. W. POSTMA†

ABSTRACT

A periodic structure consisting of alternating plane, parallel, isotropic, and homogeneous elastic layers can be replaced by a homogeneous, transversely isotropic material as far as its gross-scale elastic behavior is concerned. The five elastic moduli of the equivalent transversely isotropic medium are accordingly expressed in terms of the elastic properties and the ratio of the thicknesses of the individual isotropic layers. Imposing the condition that the Lamé constants in the isotropic layers are positive, a number of inequalities are derived, showing limitations of the values the five elastic constants of the anisotropic medium can assume. The wave equation is derived from the stress-strain relations and the equation of motion. It is shown that there are in general three characteristic velocities, all functions of the direction of the propagation. A graphical procedure is given for the derivation of these characteristic velocities from the five elastic moduli and the average density of the medium. A few numerical examples are presented in which the graphical procedure is applied. Examples are given of cases which are likely to be encountered in nature, as well as of cases which emphasize the peculiarities which may occur for a physically possible, but less likely, choice of properties of the constituent isotropic layers. The concept of a wave surface is briefly discussed. It is indicated that one branch of a wave surface may have cusps. Finally, a few remarks are made on the possible application of this theory to actual field problems.

INTRODUCTION

It has been recognized since early in the history of seismic exploration that the convenient assumption of isotropy in the medium in which waves propagate is not always justified. It was found in several instances that the velocity of seismic waves in the upper part of the earth's crust varies with the direction of propagation (see, for instance, McCollum and Snell, 1947). In recent years increasing emphasis has been placed on this lack of isotropy. Among recent papers dealing with the effect of anisotropy on the propagation of seismic waves are those by Uhrig and Van Melle (1955), Hagedoorn (1954), and Cholet and Richard (1954). In this paper, we shall investigate the extent to which anisotropy can be attributed to layering.

In this connection, it may be useful to dwell for a moment on the basic concepts of the theory of elasticity. This theory refers to continuous media. An atomic structure of matter is a concept alien to the conventional theory of elasticity. The description of phenomena by this theory is only appropriate when we may suppose that a so-called infinitesimal element still contains a large number of atoms or molecules. Most materials present in the ground consist of a large number of crystals plus fluid, gaseous, and amorphous solid constituents. In a crystal we always find some kind of anisotropy. The individual crystals may be of different kinds and may have more or less random orientation. When the crystals have completely random orientation and when they are evenly distributed in the medi-

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um, the elastic behavior of the whole complex may be described as isotropic. This conception implies that the smallest elements of matter to be considered contain a good sampling of all constituent parts. When for some reason or other the orientation is not completely at random, a certain measure of anisotropy will be found. For example, metamorphic rocks may exhibit considerable anisotropy. Or the manner in which the materials are formed and the way their constituents are arranged during the geological processes involved in their formation may result in a seismically anisotropic medium.

A layered structure can be regarded as an anisotropic medium of the latter type. We shall, in this paper, consider a formation consisting of alternating plane, parallel layers of materials which on a smaller scale can be regarded as isotropic. In considering such a material as a homogeneous anisotropic medium, we must suppose that an elementary volume contains a large number of layers. The theory then leads to the type of anisotropy known as transverse isotropy.

In order to find a connection between the properties and thicknesses of the isotropic layers and the equivalent homogeneous, transversely isotropic medium, we may proceed in two ways. One way, which we shall follow here, involves the establishment of stress-strain relations for an elementary portion of the layered medium. With the help of these relations and the equations of motion, we can derive equations describing the propagation of plane waves. The velocity of these plane waves will turn out to be a function of the direction of the normal to the wave fronts (or, as the case may be, planes of equal phase).

The second approach is to consider plane harmonic waves in the isotropic layers (Thompson, 1950). These waves are reflected and transmitted at the various interfaces. It is possible to assign a phase velocity to the resultant wave motion. In the limit when the ratio of the thicknesses of the layers to the wavelengths approaches zero, the phase velocity should approach the velocity of propagation found by the method described in the previous paragraph. This expectation has been verified for the case of plane wave propagation perpendicular to the layering.

The second kind of derivation has the advantage of showing the degree of approximation involved with finite ratios of layer thicknesses to wavelength. The first kind has the advantage of simplicity, but yields only a limiting value.

Our calculations are restricted to the case where there are only two kinds of isotropic layers, which alternate and therefore form a periodic structure. It is realized, of course, that such periodicity would only rarely occur in nature, but this model will serve the main purpose of this paper, namely to develop a basis for estimating the degree of anisotropy which can be attributed to a layered structure of sediments.

After this paper was originally written as a company report for the Bataafsche Petroleum Maatschappij and the Shell Oil Company, an article was published by Risnichenko (1949) developing essentially the same type of argument. The writer feels justified in publishing this paper nevertheless, first because it covers

a somewhat wider range than that by Risnichenko, and secondly because the latter's paper is in Russian, which makes it less accessible.[1]

STRESS-STRAIN RELATION IN A TRANSVERSELY ISOTROPIC AND IN A STRATIFIED MEDIUM

In a transversely isotropic medium, all directions making the same angle with a certain axis of symmetry are equivalent. Taking the axis of symmetry as the z axis and supposing Hooke's law to be valid, it is then required that the coefficients in the relations between the components of stress and strain are invariant with respect to rotations of the coordinate system around the z axis. When we express, in the notation of Love (1934, art. 66), Hooke's law by the following set of equations

$$\begin{aligned} X_x &= c_{11}e_{xx} + c_{12}e_{yy} + c_{13}e_{zz} + c_{14}e_{yz} + c_{15}e_{zx} + c_{16}e_{xy} \\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ Y_z &= c_{41}e_{xx} + c_{42}e_{yy} + c_{43}e_{zz} + c_{44}e_{yz} + c_{45}e_{zx} + c_{46}e_{xy} \\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots \end{aligned} \tag{1}$$

in which expressions $c_{ij}=c_{ji}(i, j=1, 2 \cdots, 6)$, the invariance mentioned leads to the following array of the coefficients of equation (1) (Love, 1934, art. 109):

$$\begin{array}{cccccc} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \dfrac{c_{11}-c_{12}}{2} \end{array} \tag{2}$$

The meaning of the various symbols is:

X_x = the normal component of the traction across a surface element perpendicular to the x axis, etc.

Y_z = the tangential component parallel to the y axis of the traction across a surface element perpendicular to the z axis, etc.

We observe that $Y_z=Z_y$ (Love, 1934, art. 47);

$$e_{xx}=\frac{\partial u}{\partial x}; \qquad e_{yy}=\frac{\partial v}{\partial y}; \qquad e_{zz}=\frac{\partial w}{\partial z};$$

$$e_{yz}=\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}; \qquad e_{zx}=\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}; \qquad e_{xy}=\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y},$$

[1] The reader is also referred to a paper on the same subject by White and Angona (1955) which was published shortly after this paper was submitted.—*The Editor.*

where u, v, w are the components of the displacement.

e_{xx} is the linear dilatation of line elements in the direction of the x axis in the unstrained state.

e_{yz} is the decrease of the angle between two line elements, which are parallel to the y and z axes in the unstrained state (Love, 1934, art. 10).

In a transversely isotropic medium, five coefficients (in our case c_{11}, c_{12}, c_{13}, c_{33}, c_{44}) are independent, compared with two in an isotropic medium, where $c_{11} = c_{33} = \lambda + 2\mu$; $c_{12} = c_{13} = \lambda$; $c_{44} = \mu$.

Consider now a stratified medium consisting of a large number of alternating plane, parallel layers of two homogeneous, isotropic materials for which the elastic behavior is given by Lamé's constants λ_1 and μ_1, and λ_2 and μ_2, respectively. The

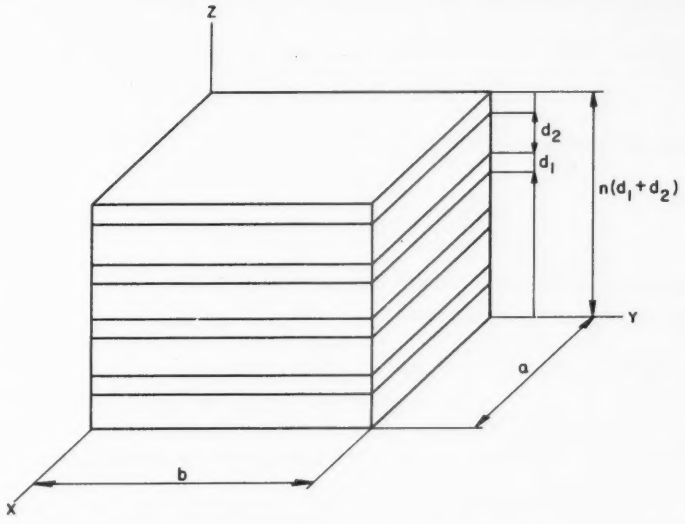

FIG. 1. Elementary volume of stratified medium.

layer thickness for the first material is d_1; for the second it is d_2. Take the z axis perpendicular to and the x and y axes parallel to the layers and consider an elementary rectangular parallelopiped with faces parallel to the coordinate planes. Let the height of the parallelopiped be $n(d_1+d_2)$, where n is an integer, and let the length and width be a and b respectively (Figure 1).

Suppose that on the faces perpendicular to the z axis a traction Z_z is exerted and that there are no tangential components Y_z and X_z. On the faces perpendicular to the x axis we also have only normal tractions, *viz.*, a normal traction X_{x1} on the layers d_1 and a normal traction X_{x2} on the layers d_2. Similarly, we have on the faces perpendicular to the y axis normal tractions Y_{y1} and Y_{y2}. The normal tractions X_{x1}, X_{x2}, Y_{y1}, Y_{y2} are such that $e_{xx1} = e_{xx2} = e_{xx}$ and $e_{yy1} = e_{yy2} = e_{yy}$, where e_{xx1} is the linear dilatation of a line element in the direction of the x axis in the layers d_1, etc. This restriction is necessary to insure the continuity of the displace-

ment as a function of the radius vector. The linear dilatation of a linear element parallel to the z axis in the d_1 layers is e_{zz1}, in the d_2 layers it is e_{zz2}. In general $e_{zz1} \neq e_{zz2}$.

In the first isotropic medium Hooke's law gives:

$$\begin{aligned} X_{x1} &= (\lambda_1 + 2\mu_1)e_{xx} + \lambda_1 e_{yy} + \lambda_1 e_{zz1} \\ Y_{y1} &= \lambda_1 e_{xx} + (\lambda_1 + 2\mu_1)e_{yy} + \lambda_1 e_{zz1} \\ Z_z &= \lambda_1 e_{xx} + \lambda_1 e_{yy} + (\lambda_1 + 2\mu_1)e_{zz1}. \end{aligned} \tag{3a}$$

The equations for the second isotropic layer are obtained by replacing the index 1 by the index 2. We shall designate this set of equations as (3b).
The average traction on a face perpendicular to the x axis becomes

$$\left.\begin{aligned} X_x &= \frac{d_1 X_{x1} + d_2 X_{x2}}{d_1 + d_2}, \\ \text{and on a face perpendicular to the } y \text{ axis,} & \\ Y_y &= \frac{d_1 Y_{y1} + d_2 Y_{y2}}{d_1 + d_2}, \end{aligned}\right\} \tag{4}$$

while the traction on the face perpendicular to the z axis is Z_z.

From (3a), (3b), and (4) we find:

$$\begin{aligned} (d_1 + d_2)X_x &= e_{xx}[d_1(\lambda_1 + 2\mu_1) + d_2(\lambda_2 + 2\mu_2)] \\ &\quad + e_{yy}(\lambda_1 d_1 + \lambda_2 d_2) + e_{zz1}\lambda_1 d_1 + e_{zz2}\lambda_2 d_2 \\ (d_1 + d_2)Y_y &= e_{xx}(\lambda_1 d_1 + \lambda_2 d_2) + e_{yy}[d_1(\lambda_1 + 2\mu_1) + d_2(\lambda_2 + 2\mu_2)] \\ &\quad + e_{zz1}\lambda_1 d_1 + e_{zz2}\lambda_2 d_2 \\ (d_1 + d_2)Z_z &= e_{xx}(\lambda_1 d_1 + \lambda_2 d_2) + e_{yy}(\lambda_1 d_1 + \lambda_2 d_2) \\ &\quad + e_{zz1}d_1(\lambda_1 + 2\mu_1) + e_{zz2}d_2(\lambda_2 + 2\mu_2). \end{aligned} \tag{5}$$

We define e_{zz} by

$$(d_1 + d_2)e_{zz} = d_1 e_{zz1} + d_2 e_{zz2}, \tag{6}$$

where e_{zz} is the over-all dilatation of a linear element parallel to the z axis, which contains an equal number of sections through the layers d_1 and d_2.

From the last equations of (3a) and (3b) and (6), we find:

$$e_{zz1} = \frac{(d_1 + d_2)(\lambda_2 + 2\mu_2)e_{zz} - (\lambda_1 - \lambda_2)(e_{xx} + e_{yy})d_2}{d_1(\lambda_2 + 2\mu_2) + d_2(\lambda_1 + 2\mu_1)}$$

$$e_{zz2} = \frac{(d_1 + d_2)(\lambda_1 + 2\mu_1)e_{zz} + (\lambda_1 - \lambda_2)(e_{xx} + e_{yy})d_1}{d_1(\lambda_2 + 2\mu_2) + d_2(\lambda_1 + 2\mu_1)}.$$

Substituting this result in (5) we arrive at:

$$X_x = e_{xx}\frac{(d_1+d_2)^2(\lambda_1+2\mu_1)(\lambda_2+2\mu_2)+d_1d_2\{[(\lambda_1+2\mu_1)-(\lambda_2+2\mu_2)]^2-(\lambda_1-\lambda_2)^2\}}{D}$$
$$+e_{yy}\frac{\lambda_1\lambda_2(d_1+d_2)^2+2(\lambda_1d_1+\lambda_2d_2)(\mu_2d_1+\mu_1d_2)}{D}$$
$$+e_{zz}\frac{(d_1+d_2)[\lambda_1d_1(\lambda_2+2\mu_2)+\lambda_2d_2(\lambda_1+2\mu_1)]}{D}$$
$$Y_y = e_{xx}\frac{\lambda_1\lambda_2(d_1+d_2)^2+2(\lambda_1d_1+\lambda_2d_2)(\mu_2d_1+\mu_1d_2)}{D}$$
$$+e_{yy}\frac{(d_1+d_2)^2(\lambda_1+2\mu_1)(\lambda_2+2\mu_2)+d_1d_2\{[(\lambda_1+2\mu_1)-(\lambda_2+2\mu_2)]^2-(\lambda_1-\lambda_2)^2\}}{D}$$
$$+e_{zz}\frac{(d_1+d_2)[\lambda_1d_1(\lambda_2+2\mu_2)+\lambda_2d_2(\lambda_1+2\mu_1)]}{D}$$
$$Z_z = (e_{xx}+e_{yy})\frac{(d_1+d_2)[\lambda_1d_1(\lambda_2+2\mu_2)+\lambda_2d_2(\lambda_1+2\mu_1)]}{D}$$
$$+e_{zz}\frac{(d_1+d_2)^2(\lambda_1+2\mu_1)(\lambda_2+2\mu_2)}{D}.$$

D is written for $(d_1+d_2)[d_1(\lambda_2+2\mu_2)+d_2(\lambda_1+2\mu_1)]$.

Proceeding in the same way by applying to the faces perpendicular to the z axis a tangential traction Y_z (Figure 2), we have:

$$(d_1+d_2)e_{yz} = d_1e_{yz1}+d_2e_{yz2}$$
$$\mu_1e_{yz1} = Y_z; \qquad \mu_2e_{yz2} = Y_z$$
$$\therefore\ (d_1+d_2)e_{yz} = \left[\frac{d_1}{\mu_1}+\frac{d_2}{\mu_2}\right]Y_z; \qquad \therefore\ Y_z = \frac{(d_1+d_2)\mu_1\mu_2}{d_1\mu_2+d_2\mu_1}e_{yz}.$$

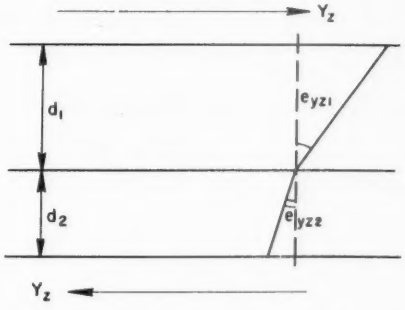

FIG. 2. Tangential stress and corresponding strain.

Similarly we find:

$$(d_1 + d_2)e_{zz} = \left[\frac{d_1}{\mu_1} + \frac{d_2}{\mu_2}\right] X_z. \qquad \therefore \; X_z = \frac{(d_1 + d_2)\mu_1\mu_2}{d_1\mu_2 + d_2\mu_1} e_{zz}.$$

Finally applying a tangential force $X_{y1}ad_1$ to the faces perpendicular to the y axis of the d_1 layers and a tangential force $X_{y2}ad_2$ to the corresponding faces of the d_2 layers and realizing that e_{xy1} must be equal to e_{xy2} in order to insure the continuity of the displacement, we find that $\mu_1 e_{xy} = X_{y1}$; $\mu_2 e_{xy} = X_{y2}$, so that when X_y is the average tangential traction on the parallelopiped,

$$X_y(d_1 + d_2) = X_{y1}d_1 + X_{y2}d_2 = e_{xy}(\mu_1 d_1 + \mu_2 d_2) \quad \therefore \; X_y = \frac{\mu_1 d_1 + \mu_2 d_2}{d_1 + d_2} e_{xy}.$$

Comparing these results with (2) we see that, when viewed on a proper scale, the layered medium may be considered as transversely isotropic. We find:

$$\begin{aligned}
c_{11} &= \frac{1}{D}\left\{(d_1+d_2)^2(\lambda_1+2\mu_1)(\lambda_2+2\mu_2)+4d_1d_2(\mu_1-\mu_2)\left[(\lambda_1+\mu_1)-(\lambda_2+\mu_2)\right]\right\} \\
c_{12} &= \frac{1}{D}\left\{(d_1+d_2)^2\lambda_1\lambda_2+2(\lambda_1d_1+\lambda_2d_2)(\mu_2d_1+\mu_1d_2)\right\} \\
c_{13} &= \frac{1}{D}\left\{(d_1+d_2)\left[\lambda_1d_1(\lambda_2+2\mu_2)+\lambda_2d_2(\lambda_1+2\mu_1)\right]\right\} \\
c_{33} &= \frac{1}{D}\left\{(d_1+d_2)^2(\lambda_1+2\mu_1)(\lambda_2+2\mu_2)\right\} \\
c_{44} &= \frac{(d_1+d_2)\mu_1\mu_2}{d_1\mu_2+d_2\mu_1} \\
c_{66} &= \frac{\mu_1d_1+\mu_2d_2}{d_1+d_2}.
\end{aligned} \tag{7}$$

Between c_{11}, c_{12}, and c_{66} there exists the relation $c_{66} = (c_{11} - c_{12})/2$, as becomes apparent by substitution. Here also there are five independent coefficients. The values of c_{11} and c_{33} are in agreement with those found by Risnichenko (1949).

LIMITATIONS OF THE VALUES OF THE COEFFICIENTS OF A LAYERED MEDIUM

The coefficients c_{11}, c_{12}, c_{13}, c_{33}, c_{44}, c_{66}, for a general transversely isotropic medium are subject to some restrictions. Rudzki (1911) gives the following inequalities:

$$\begin{aligned}
&c_{11},\, c_{33},\, c_{44},\, c_{66} > 0, \\
&c_{11} - c_{44} > 0 \qquad c_{11} - c_{66} > 0 \qquad c_{33}(c_{11} - c_{66}) > c_{13}^2 \\
&c_{33} - c_{44} > 0 \qquad c_{33} - c_{66} > 0.
\end{aligned}$$

We shall now investigate the conditions satisfied by the coefficients c_{11}, c_{12}, c_{13}, c_{33}, c_{44}, c_{66} as defined by equation (7). We shall assume that λ_1, λ_2, μ_1, and μ_2 are positive quantities;[2] c_1, c_{13}, c_{33}, c_{44}, c_{66} are seen to be positive. Since $c_{11}=c_{12}+2c_{66}$, it is evident that $c_{11}^2>0$. Furthermore, $c_{11}>c_{66}$.

$$c_{33}-c_{44}=(d_1+d_2)\left(\frac{1}{\dfrac{d_1}{\lambda_1+2\mu_1}+\dfrac{d_2}{\lambda_2+2\mu_2}}-\frac{1}{\dfrac{d_1}{\mu_1}+\dfrac{d_2}{\mu_2}}\right)>0$$

$$c_{44}-c_{66}=-\frac{d_1d_2}{d_1+d_2}\,\frac{(\mu_1-\mu_2)^2}{d_1\mu_2+d_2\mu_1}\leqq 0.$$

The equality sign is valid when $\mu_1=\mu_2$. In that case $c_{44}=c_{66}=\mu_1=\mu_2=\mu$. Since $c_{11}-c_{66}>0$, certainly $c_{11}-c_{44}>0$.

We can choose the constants at our disposal, which are d_1/d_2, λ_1, μ_1, λ_2, μ_2, so that $c_{33}-c_{66}<0$. For instance, letting them have the respective values 1, λ_1, 0, 0, $4\lambda_1$, we get:

$$c_{33}-c_{66}=\frac{d_1+d_2}{\dfrac{d_1}{\lambda_1+2\mu_1}+\dfrac{d_2}{\lambda_2+2\mu_2}}-\frac{\mu_1d_1+\mu_2d_2}{d_1+d_2}$$

$$\to\frac{2}{\dfrac{1}{\lambda_1}+\dfrac{1}{8\lambda_1}}-\frac{4\lambda_1}{2}=-\lambda_1\frac{2}{9}<0.$$

This is in contradiction with one of the conditions given by Rudzki.

The values chosen are not likely to occur in nature, but they are physically possible. The expression $(c_{11}-c_{44})(c_{33}-c_{44})-(c_{13}+c_{44})^2$ will prove to be important. After a somewhat lengthy calculation, which will not be repeated here, we find that

$$(c_{11}-c_{44})(c_{33}-c_{44})-(c_{13}+c_{44})^2=\frac{4d_1d_2(\mu_1-\mu_2)^2(\lambda_1+\mu_1)(\lambda_2+\mu_2)}{(d_1\mu_2+d_2\mu_1)\left[d_1(\lambda_2+2\mu_2)+d_2(\lambda_1+2\mu_1)\right]},$$

which is always larger than zero, except for $\mu_1=\mu_2$, in which case it becomes zero.

Equally important is the expression

$$\left(\frac{c_{11}+c_{33}}{2}-c_{44}\right)-(c_{13}+c_{44})=\frac{c_{11}-2c_{13}+c_{33}}{2}-2c_{44}.$$

[2] For the isotropic materials in the earth this is always the case. It should be mentioned, however, that the requirements for stability are less stringent. These are $\mu>0$ and $\lambda>-\frac{2}{3}\mu$.

On substitution of the values in (7) we find that

$$\frac{c_{11} - 2c_{13} + c_{33}}{2} - 2c_{44}$$

$$= 2\frac{d_1 d_2}{d_1 + d_2}(\mu_1 - \mu_2)^2 \frac{d_1(\lambda_2 + \mu_2) + d_2(\lambda_1 + \mu_1)}{[d_1(\lambda_2 + 2\mu_2) + d_2(\lambda_1 + 2\mu_1)](d_1\mu_2 + d_2\mu_1)} \geqq 0.$$

The equality sign corresponds to the special case $\mu_1 = \mu_2$. The expression

$$c_{11} - c_{33} = \frac{4d_1 d_2}{d_1 + d_2}(\mu_1 - \mu_2)\frac{(\lambda_1 + \mu_1) - (\lambda_2 + \mu_2)}{d_1(\lambda_2 + 2\mu_2) + d_2(\lambda_1 + 2\mu_1)}$$

may be positive or negative: positive when $\mu_1 > \mu_2$ and simultaneously $\lambda_1 + \mu_1 > \lambda_2 + \mu_2$, or when $\mu_1 < \mu_2$ and simultaneously $\lambda_1 + \mu_1 < \lambda_2 + \mu_2$; and negative when $\mu_1 > \mu_2$ while $\lambda_1 + \mu_1 < \lambda_2 + \mu_2$ or when $\mu_1 < \mu_2$ while $\lambda_1 + \mu_1 > \lambda_2 + \mu_2$.

When either $\mu_1 = \mu_2$ or $\lambda_1 + \mu_1 = \lambda_2 + \mu_2$, c_{11} equals c_{33}. c_{11}/c_{33} can have arbitrarily large values as can be seen from the following expression:

$$\frac{c_{11}}{c_{33}} = 1 + \frac{4d_1 d_2}{(d_1 + d_2)^2}(\mu_1 - \mu_2)\frac{(\lambda_1 + \mu_1) - (\lambda_2 + \mu_2)}{(\lambda_1 + 2\lambda_2)(\lambda_2 + 2\mu_2)}.$$

Let $\lambda_1 = n\lambda_2$ and $\mu_1 = n\mu_2$, a condition that is always possible, in which case both media have the same Poisson's ratio; then

$$\frac{c_{11}}{c_{33}} \to 1 + \frac{4d_1 d_2}{(d_1 + d_2)^2}\frac{\mu_2(\lambda_2 + \mu_2)}{(\lambda_2 + 2\mu_2)^2}\frac{(n-1)^2}{n},$$

which for $n \to \infty$ grows beyond any limit.

It can be shown that $(c_{11}/c_{33}) > \frac{1}{2}$. For example, if $\mu_1 = \lambda_2 = 0$ and $d_1 = d_2$, we have

$$\frac{c_{11}}{c_{33}} = 1 - \frac{\lambda_1 - \mu_2}{2\lambda_1} = \frac{1}{2} + \frac{\mu_2}{\lambda_1}.$$

For the case $\mu_1 = \mu_2 = \mu$ we have the remarkable result that

$$c_{11} = c_{33} = \frac{d_1 + d_2}{\dfrac{d_1}{\lambda_1 + 2\mu} + \dfrac{d_2}{\lambda_2 + 2\mu}}; \qquad c_{12} = c_{13} = \frac{\lambda_1\dfrac{d_1}{\lambda_1 + 2\mu} + \lambda_2\dfrac{d_2}{\lambda_2 + 2\mu}}{\dfrac{d_1}{\lambda_1 + 2\mu} + \dfrac{d_2}{\lambda_2 + 2\mu}};$$

$$c_{44} = c_{66} = \mu.$$

The medium behaves as an isotropic medium in which

$$\lambda = \frac{\lambda_1\dfrac{d_1}{\lambda_1 + 2\mu} + \lambda_2\dfrac{d_2}{\lambda_2 + 2\mu}}{\dfrac{d_1}{\lambda_1 + 2\mu} + \dfrac{d_2}{\lambda_2 + 2\mu}}.$$

PLANE WAVES IN A LAYERED MEDIUM

Wave propagation in an anisotropic medium in general and in a transversely isotropic medium in particular has been treated by various authors. Love (1934, art. 208) devotes a few pages to this subject in his book on elasticity. Stoneley (1949) has considered the case of transverse isotropy in more detail. In an unpublished report by Hazebroek for the Bataafsche Petroleum Maatschappij on wave propagation in an anisotropic medium, reference was made to the paper by Rudzki (1911), to whom we are indebted for a thorough investigation. Unfortunately, this paper is not readily accessible.

We shall derive the wave equation for waves in a transversely isotropic medium from the stress-strain relations (2) and the equations of motion.

The equations of motion are

$$\begin{aligned}
\frac{\partial X_x}{\partial x}+\frac{\partial X_y}{\partial y}+\frac{\partial X_z}{\partial z} &= \rho\frac{\partial^2 u}{\partial t^2}\\
\frac{\partial Y_x}{\partial x}+\frac{\partial Y_y}{\partial y}+\frac{\partial Y_z}{\partial z} &= \rho\frac{\partial^2 v}{\partial t^2}\\
\frac{\partial Z_x}{\partial x}+\frac{\partial Z_y}{\partial y}+\frac{\partial Z_z}{\partial z} &= \rho\frac{\partial^2 w}{\partial t^2}\cdot
\end{aligned} \tag{8}$$

Substituting in these equations the expressions for the components of the stress as given by Hooke's law (equation (2)), we get:

$$\begin{aligned}
c_{11}\frac{\partial^2 u}{\partial x^2}+c_{66}\frac{\partial^2 u}{\partial y^2}+c_{44}\frac{\partial^2 u}{\partial z^2}+(c_{11}-c_{66})\frac{\partial^2 v}{\partial x\partial y}+(c_{13}+c_{44})\frac{\partial^2 w}{\partial x\partial z} &= \rho\frac{\partial^2 u}{\partial t^2}\\
(c_{11}-c_{66})\frac{\partial^2 u}{\partial x\partial y}+c_{66}\frac{\partial^2 v}{\partial x^2}+c_{11}\frac{\partial^2 v}{\partial y^2}+c_{44}\frac{\partial^2 v}{\partial z^2}+(c_{13}+c_{44})\frac{\partial^2 w}{\partial y\partial z} &= \rho\frac{\partial^2 v}{\partial t^2}\\
(c_{13}+c_{44})\frac{\partial^2 u}{\partial x\partial z}+(c_{13}+c_{44})\frac{\partial^2 v}{\partial y\partial z}+c_{44}\frac{\partial^2 w}{\partial x^2}+c_{44}\frac{\partial^2 w}{\partial y^2}+c_{33}\frac{\partial^2 w}{\partial z^2} &= \rho\frac{\partial^2 w}{\partial t^2}\cdot
\end{aligned} \tag{9}$$

The value of the density ρ is given by $\rho=(\rho_1 d_1+\rho_2 d_2)/(d_1+d_2)$ where ρ_1 and ρ_2 are the respective densities in the d_1 and d_2 layers.

We now try a solution representing plane waves; we may restrict ourselves to waves perpendicular to the coordinate plane $y=0$, for the axial symmetry around the z axis guarantees the similarity of wave fronts perpendicular to any meridian plane. The wave motion is then described by equations of the form:

$$\begin{aligned}
u &= u_0 f(x\cos\phi+z\sin\phi-Vt)\\
v &= v_0 f(x\cos\phi+z\sin\phi-Vt)\\
w &= w_0 f(x\cos\phi+z\sin\phi-Vt)
\end{aligned} \tag{10}$$

where f may be an arbitrary function of its argument (Fig. 3).

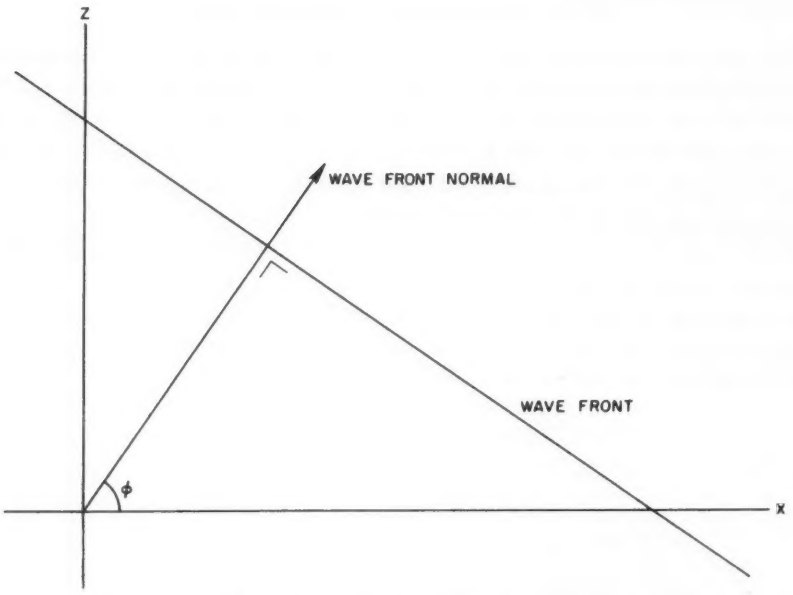

FIG. 3. Wavefront and wavefront normal. Stratification perpendicular to z-axis.

All terms in equation (9) containing $\partial/\partial y$ are zero in this case. Substituting equation (10) in equation (9) we get, after some reduction,

$$\begin{aligned}(c_{11}\cos^2\phi + c_{44}\sin^2\phi)u_0 + (c_{13}+c_{44})\sin\phi\cos\phi w_0 &= \rho V^2 u_0\\ (c_{66}\cos^2\phi + c_{44}\sin^2\phi)v_0 &= \rho V^2 v_0 \qquad (11)\\ (c_{13}+c_{44})\sin\phi\cos\phi u_0 + (c_{44}\cos^2\phi + c_{33}\sin^2\phi)w_0 &= \rho V^2 w_0.\end{aligned}$$

We see that the second equation contains the unknown v_0 only, and the first and third the unknowns u_0 and w_0 only.

One solution where u_0, v_0, and w_0 do not all simultaneously vanish is $u_0 = w_0 = 0$ and v_0 arbitrary. The condition under which this is possible is $\rho V^2 = c_{66}\cos^2\phi + c_{44}\sin^2\phi$. When $u_0 = w_0 = 0$, we deal with a plane wave in which the line of oscillation of the individual points is perpendicular to the plane $y = 0$, which stands, on account of the symmetry, for any meridian plane.

For $\phi = 0$, we find $V_3(0) = \sqrt{c_{66}/\rho}$; for $\phi = \pi/2$, $V_3(\pi/2) = \sqrt{c_{44}/\rho}$. As $c_{66} \geqq c_{44}$, $V_3(0) \geqq V_3(\pi/2)$, the equality sign holding for the case $\mu_1 = \mu_2$.

The envelope of the wavefronts corresponding to $t = 1$ with all possible values of ϕ(0 to 2π) proves to be the ellipse

$$\frac{x^2}{c_{66}/\rho} + \frac{z^2}{c_{44}/\rho} = 1. \qquad (12)$$

The wave surface (Love, 1934, art. 209) is the ellipsoid obtained by a rotation of the ellipse around the z axis.

Other solutions can be found in which $v_0=0$, and $u_0\neq 0$, $w_0\neq 0$, corresponding to plane waves where the points of the medium oscillate along straight lines in the plane $y=0$. These solutions exist when the determinant vanishes, *viz.*

$$\begin{vmatrix} c_{11}\cos^2\phi + c_{44}\sin^2\phi - \rho V^2 & (c_{13}+c_{44})\sin\phi\cos\phi \\ (c_{13}+c_{44})\sin\phi\cos\phi & c_{44}\cos^2\phi + c_{33}\sin^2\phi - \rho V^2 \end{vmatrix} = 0. \qquad (13)$$

This equation is equivalent to Stoneley's equation (10) (Stoneley, 1949).

To solve equation (13) we shall apply a graphical method in order not to commit ourselves to the handling of unwieldy expressions.

With the following substitutions,

$$c_{11}\cos^2\phi + c_{44}\sin^2\phi = a; \quad (c_{13}+c_{44})\sin\phi\cos\phi = b;$$
$$c_{44}\cos^2\phi + c_{33}\sin^2\phi = c; \quad \rho V^2 = R;$$
$$w_0/u_0 = \tan\theta,$$

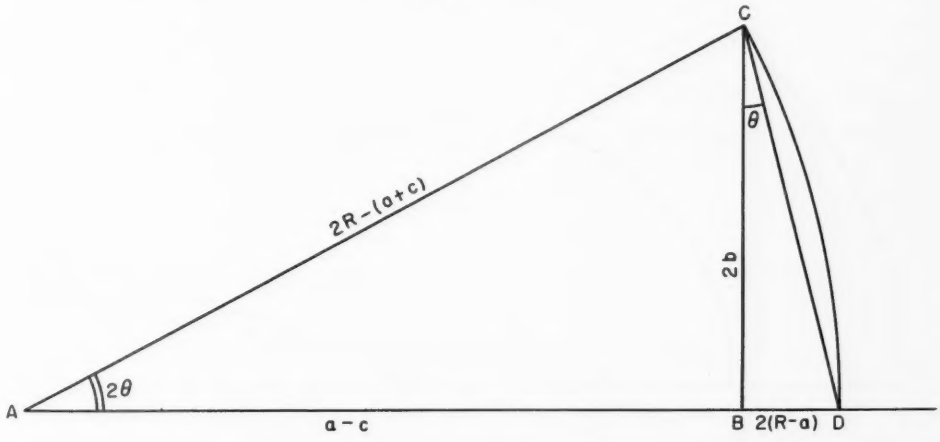

FIG. 4. Graphical representation of equations (15) and (16).

the first and third equations of (11) take the form:

$$a + b\tan\theta = R$$
$$b + c\tan\theta = R\tan\theta. \qquad (14)$$

Here θ gives the direction of the particle displacement. Elimination of θ gives:

$$\frac{R-a}{b} = \frac{b}{R-c}. \qquad (15)$$

Elimination of R gives

$$\tan\theta(a + b\tan\theta) = b + c\tan\theta$$
$$\tan 2\theta = \frac{2\tan\theta}{1-\tan^2\theta} = \frac{2b}{a-c}. \qquad (16)$$

The graphical representation of equations (15) and (16) is shown in Figure 4. We see that $AC=AD=a-c+2(R-a)=2R-(a+c)$. $a+c$ is the sum of the two roots of the quadratic equation in R (equation 15). Let these roots be R_1 and R_2 and let R_1 be the greater of the two. Then $AC=R_1-R_2$ is the absolute value of the difference of the roots.

In Figure 5, the construction of R_1-R_2 and R_1+R_2 is shown as a function of ϕ. It will readily be verified that

$$AB = a - c = \frac{c_{11} - c_{33}}{2} + \left(\frac{c_{11} + c_{33}}{2} - c_{44}\right) \cos 2\phi$$

$$BC = 2b = (c_{13} + c_{44}) \sin 2\phi$$

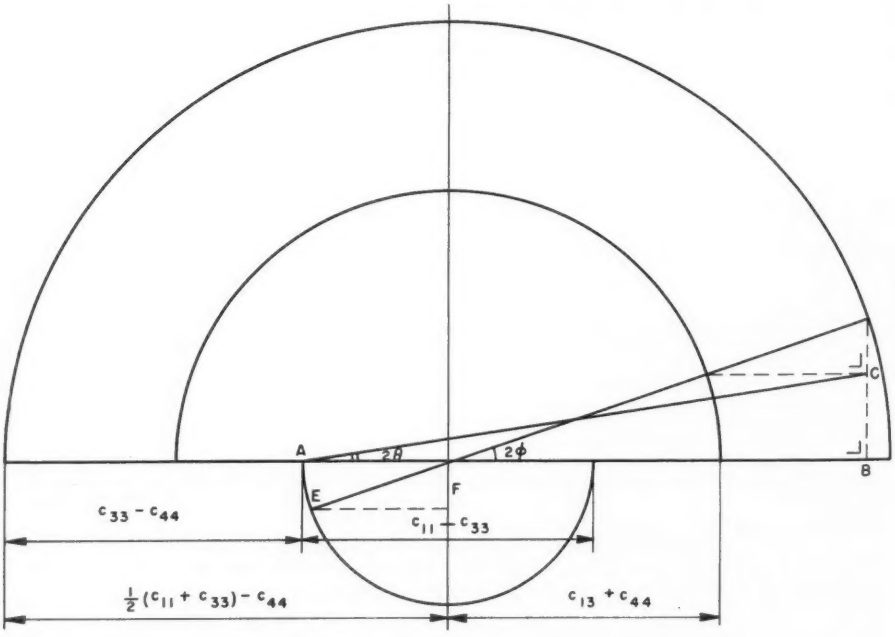

FIG. 5. Construction of the sum and difference of the roots of equation (15) from the given elastic coefficients.

and, therefore

$$AC = R_1 - R_2.$$

Also, $EF=(c_{11}-c_{33})/2 \cos 2\phi$, which yields

$$R_1 + R_2 = a + c = \frac{c_{11} + c_{33}}{2} + c_{44} + EF.$$

In the previous section we saw that $(c_{11}+c_{33})/2-c_{44}>c_{13}+c_{44}$. Therefore, the major axis of the ellipse described by C, when ϕ varies from o to π, is always horizontal. The largest value of R_1-R_2 occurs when $\phi=0$ or $\pi/2$, corresponding to $c_{11}>c_{33}$ or $c_{33}>c_{11}$.

The sum and difference of the roots being known, R_1 and R_2 can be determined without difficulty. The construction also gives θ as a function of ϕ. The values of θ corresponding to R_1 and R_2 differ by an amount $\pi/2$. When a value θ satisfies equation (16), this equation will also be satisfied by $\theta+(\pi/2)$. To determine which of the two values of θ corresponds to R_1, we consider a small value of ϕ. Then $a\sim c_{11}$; $b\sim(c_{13}+c_{44})$; $c\sim c_{44}$.

According to equation (16) we have

$$\tan 2\theta \sim \frac{(c_{13}+c_{44})2\phi}{c_{11}-c_{44}}$$

for which the following two solutions are of interest:

$$\theta_1 \sim \phi\frac{c_{13}+c_{44}}{c_{11}-c_{44}} \quad \text{and} \quad \theta_2 \sim \frac{\pi}{2}+\phi\frac{c_{13}+c_{44}}{c_{11}-c_{44}}.$$

Let $\theta=\theta_1$; then the first equation of (14) gives $R\sim c_{11}$. Let $\theta=\theta_2$; then

$$\tan\theta_2 \sim -\frac{c_{11}-c_{44}}{\phi(c_{13}+c_{44})}.$$

The first equation of (14) yields

$$R \sim c_{11}-\phi(c_{13}+c_{14})\frac{c_{11}-c_{44}}{\phi(c_{13}+c_{44})} = c_{44}.$$

The same result can be obtained from the second equation. So for $\phi=0$.

$$R_1 = c_{11}, \quad \theta = 0, \quad \text{and} \quad R_2 = c_{44}, \quad \theta = \pi/2.$$

For $\phi=\pi/2$,

$$R_1 = c_{33}, \quad \theta = \pi/2, \quad \text{and} \quad R_2 = c_{44}, \quad \theta = \pi.$$

The wave with the largest normal velocity, therefore, resembles a longitudinal wave, while the slower wave resembles a transverse wave. The waves are purely longitudinal or transverse in the directions $\phi=0$ and $\pi/2$, but not in general in other directions.

For the velocities we find $V_1(0)=\sqrt{c_{11}/\rho}$; $V_1(\pi/2)=\sqrt{c_{33}/\rho}$; $V_2(0)=\sqrt{c_{44}/\rho}$; $V_2(\pi/2)=\sqrt{c_{44}/\rho}$.

We write equation (13) in the form:

$$R^2-R\left[c_{44}+\left(\frac{c_{11}+c_{33}}{2}+\frac{c_{11}-c_{33}}{2}\cos 2\phi\right)\right]+c_{44}\left(\frac{c_{11}+c_{33}}{2}+\frac{c_{11}-c_{33}}{2}\cos 2\phi\right)$$

$$+\frac{1}{4}[(c_{11}-c_{44})(c_{33}-c_{44})-(c_{13}+c_{44})^2]\sin^2 2\phi = 0.$$

$$\therefore\ (R-c_{44})\left(R-\frac{c_{11}+c_{33}}{2}-\frac{c_{11}-c_{33}}{2}\cos 2\phi\right)$$

$$=-\frac{1}{4}[(c_{11}-c_{44})(c_{33}-c_{44})-(c_{13}+c_{44})^2]\sin^2 2\phi. \quad (13a)$$

From the results in the previous section, we see that the right-hand member is always negative when $\mu_1 \neq \mu_2$ and when $\phi \neq 0$ or $\pi/2$. Since

$$c_{44} < \frac{c_{11}+c_{33}}{2}+\frac{c_{11}-c_{33}}{2}\cos 2\phi$$

for all values of ϕ, the roots must lie between the following limits

$$c_{44} \leqq R_2 < R_1 \leqq \frac{c_{11}+c_{33}}{2}+\frac{c_{11}-c_{33}}{2}\cos 2\phi.$$

The two roots R_1 and R_2 are always distinct, for R_1-R_2 never vanishes when ϕ changes from 0 to $\pi/2$ (Figure 5).

In the exceptional case that $\mu_1=\mu_2$, the second member becomes zero and the roots are $R_1=c_{11}=c_{33}$ and $R_2=c_{44}$. They are independent of ϕ. The wave surfaces prove to be spheres with radii

$$\sqrt{\frac{c_{11}}{\rho}}=\sqrt{\frac{c_{33}}{\rho}} \quad \text{and} \quad \sqrt{\frac{c_{44}}{\rho}}.$$

NUMERICAL EXAMPLES

A few examples have been circulated on the basis of data from the literature

Eve and Keys (1929, p. 188) give the following numerical values for elastic constants of typical earth materials:

Limestone:

$$\rho = 2.69\text{–}2.72; \qquad \mu = (2.1\text{–}3.0)10^{11};$$
$$\kappa = (3.7\text{–}5.7)10^{11}; \qquad \sigma = 0.25\text{–}0.28 \text{ (c.g.s. units)}.$$

Sandstone:

$$\rho = 2.3\ (?); \qquad \mu = 0.61\cdot 10^{11};$$
$$\kappa = 1.25\cdot 10^{11}; \qquad \sigma = 0.29 \text{ (c.g.s. units)}.$$

κ is the bulk modulus; $\kappa=\lambda+\frac{2}{3}\mu$; σ is Poisson's ratio.

For a demonstration of the anisotropy under realistic conditions, we take the d_1 layers to be limestone and the d_2 layers sandstone, with the following parameters:

$$\rho_1 = 2.7; \quad \mu_1 = 2.5 \cdot 10^{11}; \quad \lambda_1 = 3.0 \cdot 10^{11}; \quad \sigma_1 = 0.273,$$

from which

$$V_{p1} = 5.44 \text{ km-sec}^{-1}; \quad V_{s1} = 3.04 \text{ km-sec}^{-1}.$$

$$\rho_2 = 2.3; \quad \mu_2 = 0.6 \cdot 10^{11}; \quad \lambda_2 = 0.8 \cdot 10^{11}; \quad \sigma_2 = 0.286,$$

from which

$$V_{p2} = 2.95 \text{ km-sec}^{-1}; \quad V_{s2} = 1.62 \text{ km-sec}^{-1}.$$

Case 1

Let $d_1 = 1$; $d_2 = 3$. (See Figure 6.) We find

$$c_{11} = 3.36 \cdot 10^{11} \text{ (dyne/cm}^2\text{)} \qquad c_{33} = 2.46 \cdot 10^{11}$$

$$c_{12} = 1.21 \cdot 10^{11} \qquad c_{44} = 0.74 \cdot 10^{11}$$

$$c_{13} = 0.97 \cdot 10^{11} \qquad c_{66} = 1.08 \cdot 10^{11}$$

$$\rho = 2.4$$

$$\sqrt{\frac{c_{11}}{\rho}} = 3.73 \text{ km-sec}^{-1}; \quad \sqrt{\frac{c_{33}}{\rho}} = 3.21 \text{ km-sec}^{-1}; \quad \sqrt{\frac{c_{44}}{\rho}} = 1.76 \text{ km-sec}^{-1};$$

$$\sqrt{\frac{c_{66}}{\rho}} = 2.12 \text{ km-sec}^{-1}.$$

Then we obtain the following data by means of the construction in Figure 5:

ϕ	V_1	V_2	V_3	(km-sec^{-1})
0 (x direction)	3.73	1.76	2.12	
$\pi/24$	3.71	1.79	2.12	
$\pi/12$	3.67	1.82	2.10	
$\pi/8$	3.62	1.87	2.07	
$\pi/6$	3.53	1.91	2.04	
$5\pi/24$	3.45	1.97	2.00	
$\pi/4$	3.36	2.00	1.95	
$7\pi/24$	3.29	2.00	1.89	
$\pi/3$	2.24	1.94	1.86	
$3\pi/8$	3.22	1.89	1.82	
$5\pi/12$	3.21	1.84	1.79	
$11\pi/24$	3.21	1.79	1.76	
$\pi/2$	3.21	1.76	1.76	

Case 2

Let $d_1 = 3$; $d_2 = 1$. (See Figure 6.)

$$c_{11} = 6.25 \cdot 10^{11} \text{ (dyne/cm}^2\text{)} \qquad c_{33} = 4.57 \cdot 10^{11}$$

$$c_{12} = 2.19 \cdot 10^{11} \qquad c_{44} = 1.40 \cdot 10^{11}$$

$$c_{13} = 1.74 \cdot 10^{11} \qquad c_{66} = 2.03 \cdot 10^{11}$$

$$\rho = 2.6$$

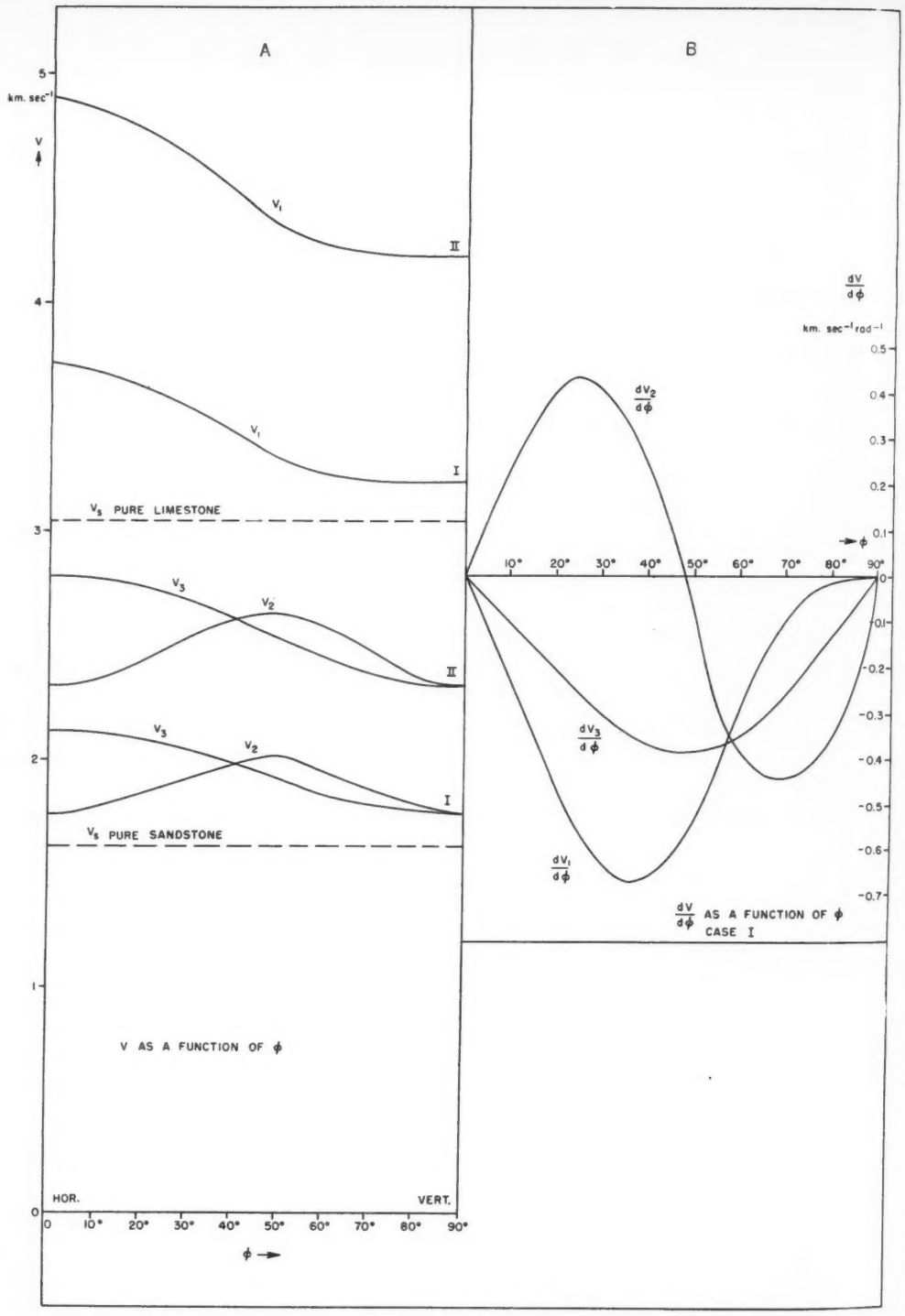

FIG. 6. (A) The velocity V of plane waves as a function of the angle ϕ included by the normal and the plane of the layers, obtained by the construction of Fig. 5.

Case I	$d_1/d_2=\frac{1}{3}$	(page 795)
Case II	$d_1/d_2=3$	(page 795)

(B) $dV/d\phi$ as a function of ϕ for Case I, obtained by graphical differentiation of the curves in (A).

$\sqrt{\frac{\overline{c_{11}}}{\rho}} = 4.90$ km-sec^{-1}; $\sqrt{\frac{\overline{c_{33}}}{\rho}} = 4.19$ km-sec^{-1}; $\sqrt{\frac{\overline{c_{44}}}{\rho}} = 2.32$ km-sec^{-1};

$\sqrt{\frac{\overline{c_{66}}}{\rho}} = 2.79$ km-sec^{-1}.

For this case we obtain:

ϕ	V_1	V_2	V_3	(km-sec^{-1})
0	4.90	2.32	2.79	
$\pi/24$	4.87	2.34	2.79	
$\pi/12$	4.82	2.39	2.77	
$\pi/8$	4.74	2.45	2.74	
$\pi/6$	4.63	2.53	2.68	
$5\pi/24$	4.52	2.59	2.63	
$\pi/4$	4.40	2.63	2.57	
$7\pi/24$	4.31	2.63	2.51	
$\pi/3$	4.24	2.57	2.45	
$3\pi/8$	4.22	2.51	2.39	
$5\pi/12$	4.20	2.41	2.34	
$11\pi/24$	4.20	2.34	2.32	
$\pi/2$	4.20	2.32	2.32	

To show the peculiarities which may occur in extreme cases we have also calculated the artificial case of layers d_1, approximately with the properties of limestone, and layers d_2, with approximately the properties of water (Figure 7).

$\rho_1 = 2.5$; $\mu_1 = 2.5 \cdot 10^{11}$; $\lambda_1 = 2.5 \cdot 10^{11}$; $\sigma_1 = 0.25$; $d_1 = 1$;

$V_{p1} = 5.48$ km-sec^{-1}; $V_{s1} = 3.16$ km-sec^{-1}.

$\rho_2 = 1$; $\mu_2 = 0$; $\lambda_2 = 0.25 \cdot 10^{11}$; $\sigma_2 = 0.50$; $d_2 = 0.01$;

$V_{p2} = 1.58$ km-sec^{-1}; $V_{s2} = 0$.

$c_{11} = 7.25 \cdot 10^{11}$ (dyne/cm^2) $c_{33} = 5.82 \cdot 10^{11}$

$c_{12} = 2.33 \cdot 10^{11}$ $c_{44} = 0$

$c_{13} = 1.98 \cdot 10^{11}$ $c_{66} = 2.47 \cdot 10^{11}$

$\rho = 2.48$

$\sqrt{\frac{\overline{c_{11}}}{\rho}} = 5.41$ km-sec^{-1}; $\sqrt{\frac{\overline{c_{33}}}{\rho}} = 4.84$ km-sec^{-1}; $\sqrt{\frac{\overline{c_{44}}}{\rho}} = 0$;

$\sqrt{\frac{\overline{c_{66}}}{2}} = 3.16$ km-sec^{-1}.

We obtain the following results for this case:

ϕ	V_1	V_2	V_3	(km-sec^{-1})
0	5.41	0	3.16	
$\pi/24$	5.36	0.63	3.13	
$\pi/12$	5.25	1.14	3.06	
$\pi/8$	5.04	1.73	2.94	
$\pi/6$	4.76	2.28	2.73	
$5\pi/24$	4.45	2.88	2.50	
$\pi/4$	4.22	3.03	2.24	
$7\pi/24$	4.18	2.97	1.92	
$\pi/3$	4.33	2.49	1.57	
$3\pi/8$	4.54	1.95	1.19	
$5\pi/12$	4.70	1.34	0.82	
$11\pi/24$	4.81	0.63	0.42	
$\pi/2$	4.84	0	0	

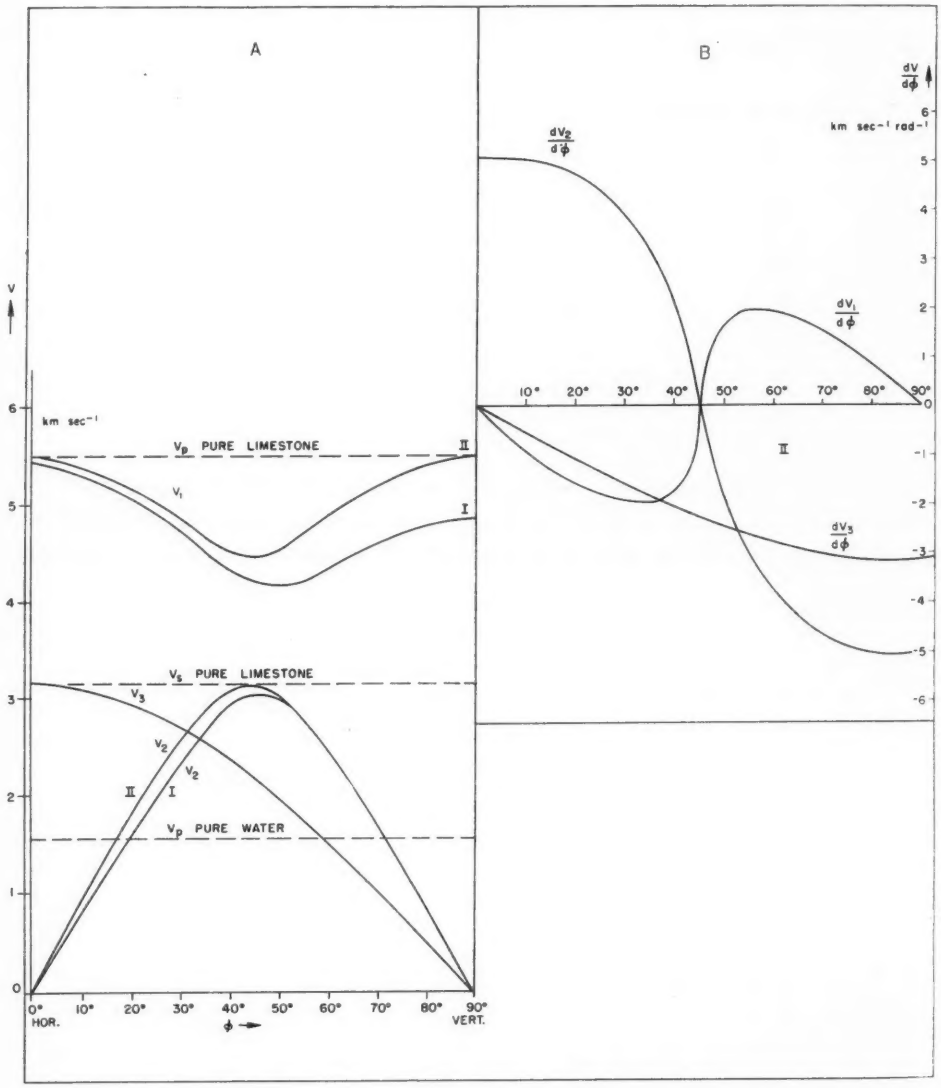

FIG. 7. (A) The velocity V of plane waves as a function of the angle ϕ included by the normal and the plane of the layers, obtained by the construction of Fig. 5. The layers are alternately limestone and water.

Case I	$d_1/d_2=100$
Case II	$d_1/d_2\rightarrow\infty$

(B) $dV/d\phi$ as a function of ϕ for Case II, obtained by graphical differentiation of the curves in (A).

Finally, the same example was calculated for $d_2\rightarrow 0$ (Figure 7). These values were obtained by direct calculation.

We find:

ϕ	V_1	V_2	V_3	
0°	5.48	0.00	3.16	(km-sec^{-1})
10°	5.41	0.89	3.12	
20°	5.18	1.75	2.98	
30°	4.87	2.52	2.74	
40°	4.53	3.07	2.43	
45°	4.47	3.16	2.23	
50°	4.53	3.07	2.03	
60°	4.87	2.52	1.59	
70°	5.18	1.75	1.08	
80°	5.41	0.89	0.53	
90°	5.48	0.00	0.00	

The influence of the vanishing of d_2 is very noticeable on V_1 and V_2 and practically nil on V_3. The assumption that c_{44} remains zero when $d_2 \to 0$ is rather unrealistic, however, from a physical point of view.

The last examples are rather extreme but they show clearly the type of phenomena we may expect in a layered medium, where one of the constituents has a low resistance against shear.

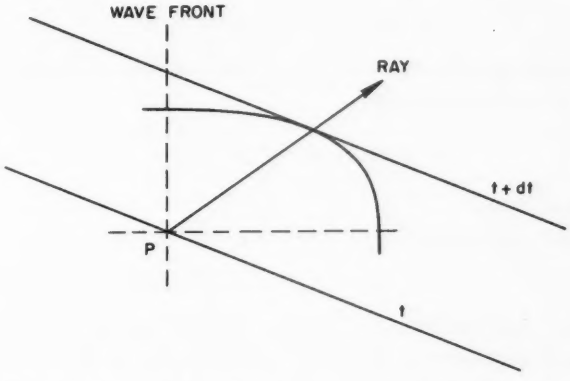

FIG. 8. Huygens' principle applied to plane wave propagation in an anisotropic medium.

WAVE SURFACES

In a previous section, we solved the equations of motion for plane waves. We can consider the propagation of these waves in the light of Huygens' principle. The secondary wavefront, emanating from a point P located on a plane wavefront at time t, is tangent to the plane wavefront at time $t+dt$. For another plane wave, with a different direction, passing through P at time t the secondary wavefront again must be tangent to the corresponding wavefront at $t+dt$, so that the secondary wavefront is found to be the envelope of the plane waves having all possible directions at time $t+dt$ (Figure 8). When the medium is homogeneous, the time interval dt need not be infinitesimal. Love calls the envelope of all plane wavefronts at $t+1$ a *wave surface* (Love, 1934, art. 209).

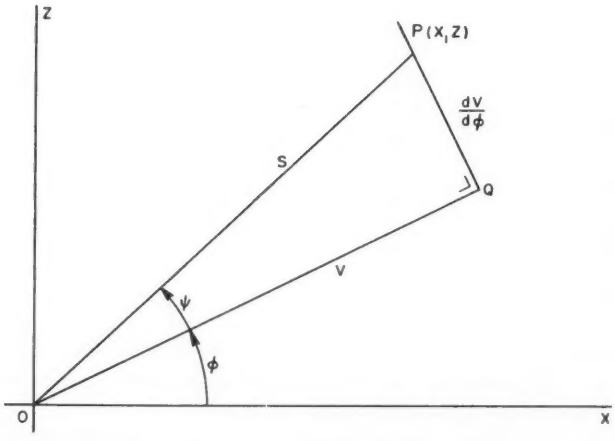

FIG. 9. Construction of the wave surface $P(x, z)$ from $V = V(\phi)$.

We can derive the equation of the wave surface by standard methods. The meridian section is the envelope of the straight lines

$$x \cos \phi + z \sin \phi = V(\phi), \tag{17}$$

where $V(\phi)$ is given as a function of ϕ by equation (13). Elimination of ϕ between equation (17) and the equation

$$-x \sin \phi + z \cos \phi = \frac{dV(\phi)}{d\phi} \tag{18}$$

yields the desired result.

Squaring and adding equations (17) and (18) leads to

$$s^2 = x^2 + z^2 = V^2 + (dV/d\phi)^2. \tag{19}$$

We construct the position of the point (x, z) of the envelope corresponding to the direction ϕ of the normal wavefront as in Figure 9. The envelope is tangent to PQ at P.

Figures 10 and 11 show plots, as obtained by this construction, of the wave surfaces and of the curves $V = V(\phi)$ for two cases of Figures 6 and 7.

The angle ψ is given by

$$\tan \psi = \frac{1}{V} \frac{dV}{d\phi}. \tag{20}$$

The envelope can have cusps. This is the case when $d(\phi+\psi)/d\phi$ changes sign when ϕ increases from 0 to $\pi/2$.

The condition for the occurrence of a cusp, therefore, is

$$1 + \frac{d\psi}{d\phi} = 1 + \frac{\dfrac{d}{d\phi}\left(\dfrac{1}{V}\dfrac{dV}{d\phi}\right)}{1 + \left(\dfrac{1}{V}\dfrac{dV}{d\phi}\right)^2} = 0.$$

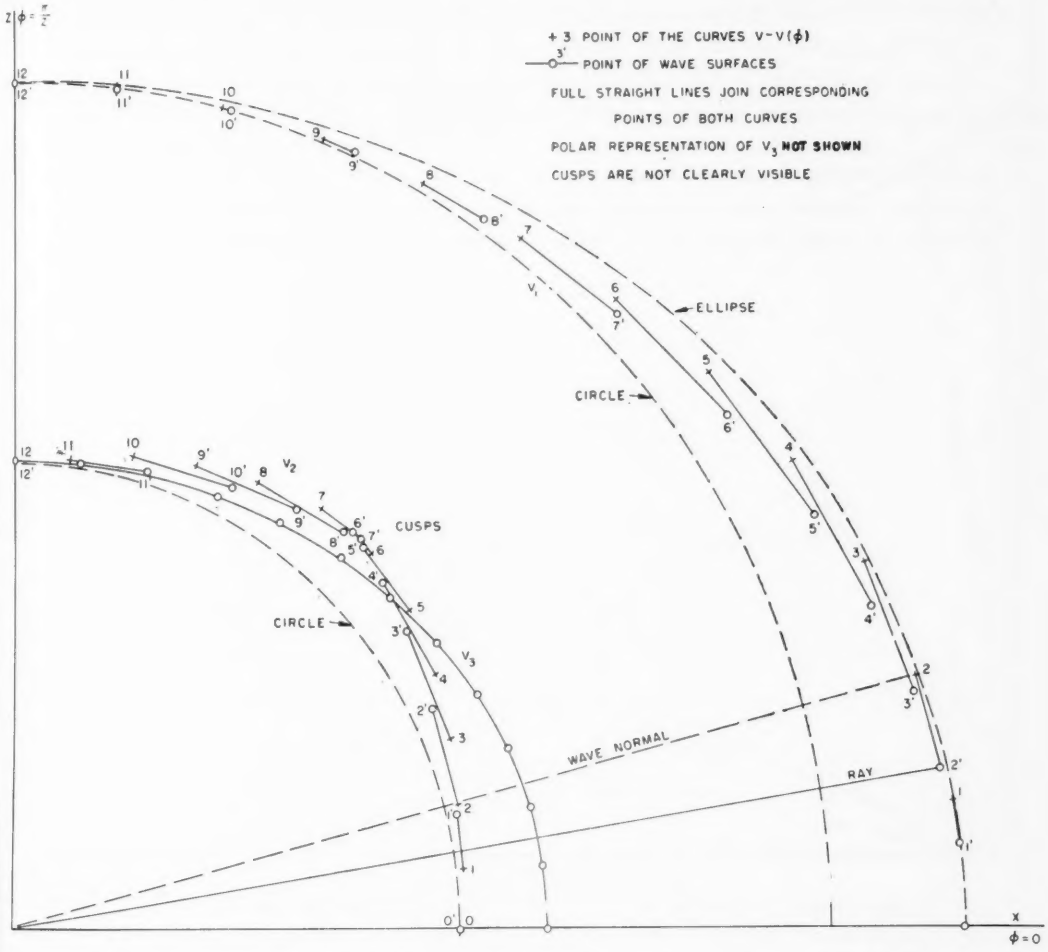

FIG. 10. Points of wave surfaces and of the curves $V = V(\phi)$, obtained from the data of Fig. 6, Case 1 by means of the construction of Fig. 9. The wave surface is not an ellipse. The wave surface V_2 shows cusps.

This can be written:

$$1 + \left(\frac{1}{V}\frac{dV}{d\phi}\right)^2 + \frac{d}{d\phi}\left(\frac{1}{V}\frac{dV}{d\phi}\right) = 0. \tag{21}$$

Corresponding to the two roots V_1 and V_2, the wave surface has two branches. The wave surface of equation (12) corresponding to the velocity V_3 of the waves for which the particle displacement is perpendicular to a meridian plane completes the picture. When the medium is isotropic, the wave surfaces V_2 and V_3 coincide and become spheres. The wave surface V_1 becomes a larger sphere concentric with the other two.

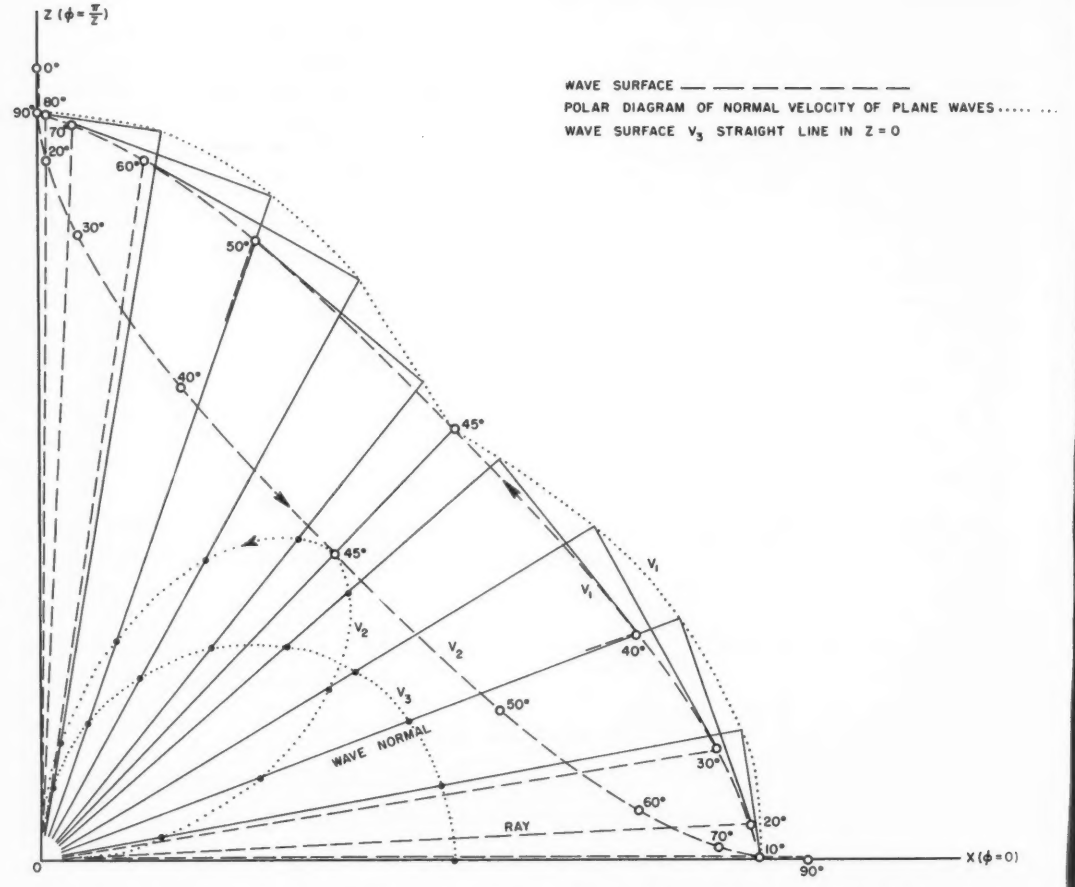

FIG. 11. Points of wave surfaces and of the curves $V = V(\phi)$, obtained from the data of Fig. 7, Case II by means of the construction of Fig. 9. The wave surface V_2 has cusps on the x and z axes. These cusps are outside the corresponding wave surface V_1.

Rudzki (1911) obtained a parametric expression for the wave surfaces V_1 and V_2 and showed that the outer one (V_1) cannot have cusps. The wave surface V_2 can have cusps. The computation becomes involved and we shall be satisfied merely to show examples of wave surfaces with and without cusps.

In Figure 12, the relations between the polar curve of $V(\phi)$ and the wave surface are shown for the case where cusps occur. Between the cusps of the wave surface, the radius vector of the latter turns in the opposite direction to that of the corresponding radius vector of the curve $V(\phi)$.

We saw that

$$c_{44} \leqq \rho V_2^2 < \rho V_1^2 \leqq \frac{c_{11} + c_{33}}{2} + \frac{c_{11} - c_{33}}{2} \cos 2\phi$$

and that the equality signs are only valid for arbitrary ϕ when the medium degenerates into an isotropic medium. If the equality signs had been valid, the wave surface for $V_1(=\sqrt{R_1/\rho})$ would have been an ellipsoid of revolution, and the wave surface V_2 a sphere. We therefore conclude that the wave surfaces of V_1 and V_2 are never ellipsoids.

Love (1934, art. 209) identifies the wave surface with the "surface bounding the disturbed portion of the medium after the lapse of one unit of time, beginning at an instant when the disturbance is confined to the immediate neighborhood

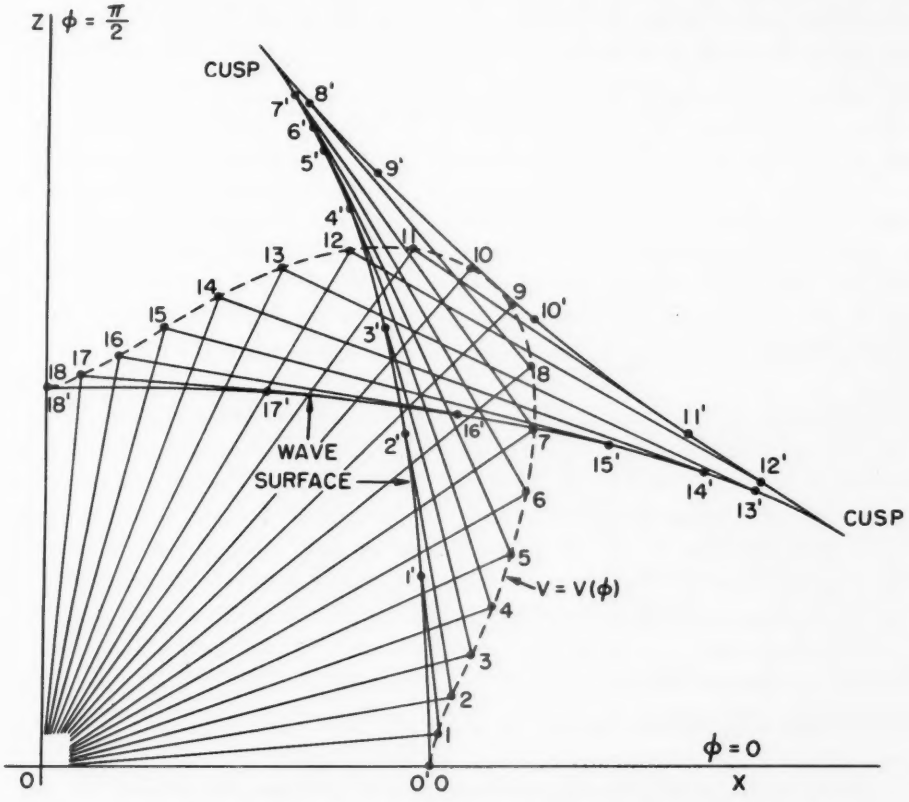

FIG. 12. Relation between a wave surface with cusps and the polar representation of the normal velocity. Corresponding points are indicated by the same numerals.

of the origin." When the wave surface has cusps, this interpretation does not have an exact meaning, as will be appreciated by consideration of Figure 12, and it appears that these simple considerations are not sufficient to produce a satisfactory picture. This difficulty does not appear when there are no cusps. However, in this case also, a closer examination, which involves the solution of the wave equation for a point source in an initially undisturbed medium, is neces-

sary. Though we cannot prove the validity of Love's interpretation of a wave surface *without* cusps, we are on fairly safe ground when we assume that in this case it is correct, for it is well known that the interpretation holds in an isotropic medium where the outer spherical wavefront actually separates the disturbed from the undisturbed region. We accept Love's interpretation when we consider the wavefront generated by a shot in a stratified medium to be a wave surface. We are usually only interested in the fastest waves. In principle the shape of the wave surface can be determined experimentally according to the scheme shown in Figure 13. A well geophone is placed in a well and shots are fired at the surface over a range of distances from the well head. The velocity along a ray can be determined (assuming straight-line paths) by measuring arrival times.

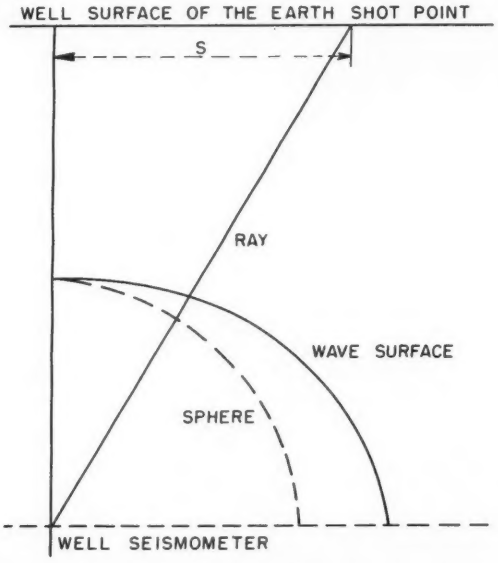

FIG. 13. Relation between the wave surface and observed travel time.

When these velocities are plotted along the rays with the well geophone as center, we obtain a graphical representation of the wave surface.

For an account of actual determinations of anisotropy, we refer to the papers by Uhrig and Van Melle, Hagedoorn, and Cholet and Richard.

We have seen that two of the wave surfaces are never ellipsoids, but from the numerical examples, it appears that in many cases they are close to being ellipsoids. In view of the approximate nature of the representation of the stratified medium by a homogeneous transversely isotropic medium, it may be justifiable to base calculations and constructions on an assumed ellipsoidal wave surface. If this is done, however, we must realize that no surface measurements alone can give us complete information on anisotropy in a horizontally stratified region. It will be necessary to have additional information from wells.

CONCLUSIONS

1) A periodic system of alternating isotropic layers of different density and elasticity can be regarded as a homogeneous transversely isotropic system as far as the propagation of elastic waves is concerned, provided that the wavelengths involved are large compared to the thicknesses of the layers.

2) In a transversely isotropic medium, as in any anisotropic medium, there are three types of waves, which may be compared to longitudinal and transverse waves of different polarization in an isotropic medium. The velocity of propagation of each of these types of waves in general depends on the direction of the normal to the wavefronts. Referring to the direction of the axis of symmetry as vertical, we find that the vertical velocity of the fastest wave, $V_1(\pi/2)$, is smaller than the larger of the P velocities of the component isotropic media. Likewise, we find that the horizontal velocity of the fastest wave, $V_1(0)$, is smaller than the larger P-wave velocity of the two component media. (This is not proved in this paper, but can readily be verified.)

3) The velocities V_1, V_2, V_3 depend not only on the velocities of the component media, but also on their densities, and the relative thicknesses of the layers.

4) The direction of the line of the particle displacement is, in general, neither in the direction of propagation nor perpendicular to it. Only for special directions is this the case. Only the waves where the particle displacement is perpendicular to a meridian plane are purely transverse.

5) The medium behaves as an isotropic medium when the rigidities μ_1 and μ_2 in the two component media are the same. The anisotropy is the more marked the greater the difference in rigidity.

6) The wave surfaces of the waves where the particles oscillate in a meridian plane are never ellipsoids. The wave surface of the waves where the particles oscillate perpendicularly to a meridian plane is an ellipsoid of revolution.

7) The wave surfaces of the faster waves where the particles oscillate in the meridian plane cannot have cusps; the wave surfaces of the slower ones can.

8) Further investigation is necessary to determine whether the wave surfaces can be regarded as surfaces bounding the disturbed and undisturbed part of the medium when the source is a point source.

9) The polar curve representing the velocity V_1 of the fastest plane waves in the direction of the normal as a function of the direction of the normal always falls inside the curve which would correspond to an ellipsoidal wave surface on the principal semi-axes

$$V_1(0) = \sqrt{\frac{\overline{c_{11}}}{\rho}} \quad \text{and} \quad V_1\left(\frac{\pi}{2}\right) = \sqrt{\frac{\overline{c_{33}}}{\rho}}.$$

Correspondingly, the curve representing the velocity V_2 as a function of ϕ in polar coordinates always falls outside the circle $V_2 = \sqrt{c_{44}/\rho}$.

10) In those cases where the wave surfaces differ but little from an ellipsoid

it becomes impossible to determine the presence of transverse isotropy from surface measurements alone where it is assumed that the layering is horizontal.

11) For the interpretation of refraction work, it can be very important to take anisotropy into account. To a lesser degree, this is true for reflection work.

ACKNOWLEDGMENTS

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MINIMUM VARIANCE IN GRAVITY ANALYSIS

PART 1: ONE-DIMENSIONAL*

WILLIAM FULLER BROWN, JR.†

ABSTRACT

Suppose that we have measurements of the vertical intensity of gravity or the magnetic field at n points; we wish to estimate a second derivative or the like at a specified point. If there were no experimental error, we could interpolate and differentiate well enough with a polynomial of degree $k-1$ $<n-1$. What shall we do when experimental error is present? The minimum-variance principle says: adjust the $n-k$ arbitrary constants of the polynomial formula so as to minimize the mean square error (variance) of the estimated quantity. By applying this principle directly, we can get "best" estimation formulas of specified degree k. We can also get "best" formulas by a least-squares method; it gives the same results as the minimum-variance method, by a theorem of mathematical statistics. The theorem furthermore enables us to estimate the variance and to choose a satisfactory value of k. For shortening the calculations, orthogonal polynomials are useful; tables of them are available in several places, and tables of their derivatives are given here. The methods are illustrated by applying them to several made-up examples of data with known random errors.

1. INTRODUCTION

Objective

In studying gravitational (or magnetic) fields on the earth's surface, we must often use the measured field intensities to calculate other quantities: for instance, second vertical derivatives. Experimental errors in the data produce large errors in the derivatives (Elkins, 1940, 1952). To improve the precision, some writers have used least-squares adjustments (Peters, 1949; Elkins, 1951), and others have used a different kind of smoothing formula (Bullard and Cooper, 1948; Grant, 1952*a*, 1952*b*); but none have fully exploited the standard techniques of mathematical statistics. My aim in this article is to do this, or at least to make a start toward it.

Basic Principle

For this purpose, I adopt a single basic principle. That principle is: minimize the mean-square random error in the calculated result. This is the "minimum-variance" principle. It is closely related to many useful techniques of statistics. These include not only the formalism of least squares, but also use of orthogonal functions (a very powerful tool), estimation of variance, significance tests, and calculation of confidence limits.

Limitation of Scope

Some physical quantities can be calculated from values of the measured vertical intensity over a *finite* region. This is true of the even vertical derivatives,

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and of the mean of the upward- and downward-continued intensities. Other physical quantities require integration over an *infinite* region. This is true of the odd vertical derivatives, and of the upward-continued intensity. This article treats only quantities of the first group.

Outline

Part 1 deals with data taken along a line. The mathematical operations are then one-dimensional, though the fields under study may be three-dimensional. Part 2 will extend the treatment to data taken on a plane.

In Part 1, the order of topics is as follows: Section 2 defines the theoretical model. Section 3 applies the minimum-variance principle directly to an illustrative problem. Section 4 relates the principle to least-squares methods. Section 5 treats orthogonal functions. Section 6 illustrates the theory by applying it to numerical examples.

2. THEORETICAL MODEL

Physical and Statistical Assumptions

We know the observed intensity at n points x_i along a line on the earth's surface. When the points are uniformly spaced at interval h, we choose the units so that $h=1$. We assume that the observed intensity g_i at point x_i is of the form

$$g_i = \eta_i + \epsilon_i, \tag{2-1}$$

where η_i is the actual intensity and ϵ_i is the experimental error. To η_i and ϵ_i we attribute the following properties.

The actual intensity η_i is a smoothly varying function of x, $\eta_i=\eta(x_i)$. Over the range of the n x_i's, $\eta(x)$ differs negligibly from a polynomial of degree $k-1$; "negligibly" means that the errors of approximation are small in comparison with the experimental error. The density of points is large enough so that n is considerably larger than k. The polynomial would therefore be overdetermined by the data if there were no experimental error. In the presence of experimental error, the extra $n-k$ observed values give us some statistical control over the error in calculated quantities.

The experimental error ϵ_i is a random variable with mean zero and variance (mean square deviation from the mean) σ^2. The errors ϵ_i, ϵ_j at different points are independent; therefore their mean product vanishes. The variance σ^2 is the same for all i's but need not be known. Most of the results to be obtained require only these properties; in particular, they do not require that the distribution of the ϵ_i's be normal (Gaussian). The significance tests and confidence limits, however, are valid only when the distribution is normal.

The Estimation Problem

The quantity to be estimated is typically a derivative of η with respect to x at a specified point: for instance, $\eta''(0)$. An estimate of $\eta''(0)$, calculated from

the observations g_i, will be represented by $\widetilde{\eta}''(0)$; the two quantities $\eta''(0)$ and $\eta''(0)$ will always be distinguished. For general discussion, a quantity to be estimated will be represented by ω and its estimate by w.

In the absence of experimental error, we could use a linear formula

$$\omega = \sum_i a_i \eta_i \tag{2-2}$$

to calculate ω. To find the a_i's, we would require that the formula be exact whenever $\eta(x)$ was a polynomial of degree $\leqq k-1$; but this requirement would impose only k conditions on the na_i's, and therefore we could set $n-k$ of the a_i's equal to zero or to arbitrary values.

In the presence of experimental error, we use an analogous formula,

$$w = \sum_i a_i g_i; \tag{2-3}$$

but instead of assigning arbitrary values to $n-k$ of the a_i's, we choose them so as to get as precise an estimate of w as we can. Explicitly, we minimize the mean-square error in w; the mean is taken over many similar experiments with data of equal precision. In statistical parlance, we minimize the population mean of the square of the deviation of w from its population mean; that is, we minimize the population variance of w.

The minimization is subject to k exactness conditions. For formula (2-3) must give the right result when there is no experimental error and when $\eta(x)$ is a polynomial of degree $\leqq k-1$; therefore the a_i's must satisfy (2-2) whenever ω is such a polynomial. To express the k exactness conditions algebraically, we may (for instance) calculate ω for each of the k functions $\eta = 1, x, x^2, \cdots, x^{k-1}$ and substitute in (2-2).

Instead of saying that formula (2-3) must give the right result when there is no experimental error, we may say that the expected value (population mean) of w must be ω. In statistical parlance, w is to be an ***unbiased*** estimate of ω if $\eta(x)$ is a polynomial of degree $\leqq k-1$.

The variance to be minimized is

$$\sigma_w^2 = \sigma^2 \sum_i a_i^2. \tag{2-4}$$

This formula holds only because the ϵ_i's are independent. Otherwise we should have to add terms $\sigma^2 \rho_{ij} a_i a_j$, where ρ_{ij} is the correlation coefficient of ϵ_i and ϵ_j.

Methods of Solution

This minimization problem leads to the theory of minimum-variance unbiased linear estimates, or best linear estimates: see Gauss (1823), Markoff (1912, p. 218 ff.), Aitken (1935), and David and Neyman (1938). The standard theory reduces the problem to a conventional least-squares problem. There are some advantages, however, in a direct application of the minimum-variance principle.

Section 3 illustrates the direct method; Section 4 deals with the relation to least-squares theory.

3. THE MINIMUM-VARIANCE METHOD

A Particular Problem

Consider the case $\omega=\eta''(0)$, $k=4$: the quantity to be estimated is the second derivative at $x=0$, and a polynomial of degree 3 is a good approximation. Equation (2-2) must be satisfied for $\eta=1$, x, x^2, or x^3; these give $\eta''(0)=0$, 0, 2, 0 respectively. The a_i's are therefore subject to the four conditions $\sum_i a_i=0$, $\sum_i a_i x_i=0$, $\sum_i a_i x_i^2=2$, $\sum_i a_i x_i^3=0$.

Assume that the points are distributed symmetrically about $x=0$; then by symmetry, $a_{-i}=a_i$ for $i\neq 0$. The second and fourth conditions have now been satisfied; the problem is therefore to minimize σ_w^2, or more simply $\sum_i a_i^2$ (see equation (2-4)), under the two conditions

$$\sum_i a_i = 0, \qquad \sum_i a_i x_i^2 = 2. \tag{3-1}$$

Solution

The minimization can be accomplished by the method of Lagrangian multipliers. For arbitrary small variations $\delta a_i (i \geqq 0)$, with $\delta a_i = \delta a_{-i}$ for $i>0$, the variation

$$\delta\left\{\frac{1}{2}\sum_i a_i^2 - L_1\sum_i a_i - L_2\sum_i a_i x_i^2\right\} = \sum_i (a_i - L_1 - L_2 x_i^2)\delta a_i$$

must vanish; L_1 and L_2 are constants, so far undetermined. Since δa_0 and $\delta a_i = \delta a_{-i} (i>0)$ are arbitrary, the coefficient of each must vanish; therefore

$$a_i = L_1 + L_2 x_i^2. \tag{3-2}$$

To determine L_1 and L_2, substitute (3-2) in (3-1):

$$\left.\begin{aligned} L_1 n + L_2\sum_i x_i^2 &= 0, \\ L_1\sum_i x_i^2 + L_2\sum_i x_i^4 &= 2. \end{aligned}\right\} \tag{3-3}$$

Solve for L_1 and L_2, and substitute the results in (3-2):

$$a_i = (2/D)\left(n x_i^2 - \sum_j x_j^2\right), \tag{3-4}$$

with

$$D = n\sum_i x_i^4 - \left(\sum_i x_i^2\right)^2. \tag{3-5}$$

The variance σ_w^2 of w, thus minimized, is

$$\sigma_w^2 = \sigma^2 \cdot 4n/D. \tag{3-6}$$

Special Cases

For five points, $x_i = i (i = -2, -1, 0, 1, 2)$, formulas (3-4)–(3-6) give $7a_i = (2, -1, -2, -1, 2)$, $\sigma_w^2/\sigma^2 = 2/7$. For seven points, $x_i = i (i = -3, -2, -1, 0, 1, 2, 3)$, they give $42a_i = (5, 0, -3, -4, -3, 0, 5)$, $\sigma_w^2/\sigma^2 = 1/21$.

An Application to Gravity

With these coefficients, we can estimate the second vertical derivative, $\partial^2\eta/\partial z^2 = -\partial^2\eta/\partial x^2 - \partial^2\eta/\partial y^2$, at the central point of a symmetric cross-shaped array. The points on the x-axis give an estimate of $\partial^2\eta/\partial x^2$, and the points on the y-axis give an estimate of $\partial^2\eta/\partial y^2$. The resulting estimate of $\partial^2\eta/\partial z^2$ is not quite the best possible from the given array, because we treat the central point inconsistently in the x and y calculations. For the 9-point array, ($x = -2$ to $+2$, $y = 0$) and ($x = 0$, $y = -2$ to $+2$), this method gives $\sigma_w/\sigma = 0.857$; for the 13-point array, ($x = -3$ to $+3$, $y = 0$) and ($x = 0$, $y = -3$ to $+3$), it gives $\sigma_w/\sigma = 0.337$. The two-dimensional method, to be developed in Part 2, gives a smaller σ_w/σ because it treats the central point consistently.

4. THE LEAST-SQUARES METHOD

The Particular Problem as an Example

Another method of solving the problem of Section 3 is: fit the data to a polynomial of the prescribed degree, by least squares, and then differentiate this polynomial. Explicitly: if $\eta(x) = \gamma_0 + \gamma_1 x + \gamma_2 x^2 + \gamma_3 x^3$ is the exact polynomial and if $\hat{\eta}(x) = c_0 + c_1 x + c_2 x^2 + c_3 x^3$ is the estimated polynomial, choose the c_r's to minimize

$$Q = \sum_i (g_i - \hat{\eta}_i)^2, \tag{4-1}$$

with $\hat{\eta}_i = \hat{\eta}(x_i)$; then estimate $\eta''(0)$ as

$$\hat{\eta}''(0) = 2c_2. \tag{4-2}$$

Is this estimate the same as the other?

For the assumed symmetrical array of points, $\sum_i x_i^r = 0$ for r odd; therefore the normal equations of the least-squares problem break up into two that determine c_0 and c_2 and two that determine c_1 and c_3. The former two are

$$\begin{aligned} c_0 n + c_2 \sum_i x_i^2 &= \sum_i g_i, \\ c_0 \sum_i x_i^2 + c_2 \sum_i x_i^4 &= \sum_i x_i^2 g_i; \end{aligned} \tag{4-3}$$

the matrix of the coefficients is the same as for equations (3-3). By solution of (4-3) and substitution of the result in (4-2),

$$\hat{\eta}''(0) = (2/D)\left(n\sum_i x_i^2 g_i - \sum_i x_i^2 \cdot \sum_i g_i\right), \tag{4-4}$$

with D given by (3-5). Equation (4-4) is of the form (2-3), with a_i given by (3-4).

Therefore the least-squares estimate is the same as the best linear estimate.

Generalization

This is a special case of a general theorem stated and proved by David and Neyman (1938). In this theorem, η_i need not be a polynomial; it may be any function of the form

$$\eta_i = \sum_{r=0}^{k-1} \gamma_r u_{ri}, \tag{4-5}$$

where, for each r, u_{ri} is a known function of $i(i=1, 2, \cdots, n)$ and γ_r is an unknown parameter. The corresponding form for ω is

$$\omega = \sum_{r=0}^{k-1} \gamma_r v_r, \tag{4-6}$$

where the v_r's are known quantities. The theorem states: the best linear estimate w of ω can be found by substituting in (4-6) the best linear estimates c_r of the γ_r's; the c_r's in turn can be found by minimizing Q, equation (4-1), with

$$\hat{\eta}_i = \sum_{r=0}^{k-1} c_r u_{ri}; \tag{4-7}$$

$\hat{\eta}_i$ is then the best linear estimate of η_i. The functions $u_{0i}, u_{1i}, \cdots, u_{(k-1)i}$ must be linearly independent with respect to the points i: that is, they must not satisfy a relation of the form $C_0u_{0i}+C_1u_{1i}+\cdots+C_{k-1}u_{(k-1)i}=0$ for $i=1, 2, \cdots, n$, except the trivial relation with $C_0=C_1=\cdots=C_{k-1}=0$. (In the example, $u_{ri}=x_i^r$; $v_2=2$, $v_r=0$ for $r\neq 2$.)

The explicit formulas for the c_r's are

$$c_r = \sum_s \beta_{rs} h_s; \tag{4-8}$$

the matrix (β_{rs}) is the inverse of the matrix (α_{rs}), whose elements are

$$\alpha_{rs} = \alpha_{sr} = \sum_i u_{ri}u_{si}, \tag{4-9}$$

and

$$h_r = \sum_i u_{ri}g_i. \tag{4-10}$$

The variance of c_r is $\sigma^2\beta_{rr}$; the covariance (mean product of deviations from the mean) of c_r and c_s is $\sigma^2\beta_{rs}$; the variance of w is

$$\sigma_w^2 = \sigma^2 \sum_r \sum_s \beta_{rs}v_r v_s. \tag{4-11}$$

Estimation of Variance and Choice of Degree

A further result of the theorem is that the minimized value of Q, Q_0, has the expected value (population mean)

$$E(Q_0) = (n - k)\sigma^2. \tag{4-12}$$

It follows that the quantity

$$s^2 = Q_0/(n - k) \tag{4-13}$$

is an unbiased estimate of σ^2. This formula is useful for estimating the precision of the data, and it can also be used to determine the degree of polynomial necessary. This degree is usually not known in advance, as has been supposed so far; it must be determined by analysis of the data. The method of doing this is as follows.

If the polynomial used is of too low degree, Q_0 will appreciably exceed the value $(n-k)\sigma^2$, because it includes not only random terms but also terms due to inadequacy of the polynomial approximation; s^2, calculated by (4-13), will appreciably exceed σ^2. But if the polynomial used is of too high degree, Q_0 will, on the average, have the value given by (4-12), and s^2 will on the average equal σ^2. Suppose, therefore, that the data are successively fitted with polynomials of degrees 0, 1, $\cdots$, $n-2$, and that in each case Q_0 and s^2 are calculated. Q_0 will decrease rapidly until all necessary polynomial terms have been included; it will then decrease, on the average, only by an amount σ^2 per term. Meanwhile, s^2 will decrease rapidly until all necessary terms have been included; it will then remain constant, except for statistical fluctuations.

The calculation just outlined is laborious when conventional least-squares methods are used, because it then requires many successive matrix inversions. To avoid these, we may use orthogonal functions (Section 5).

Consequences of Normality

All the results so far are independent of the distribution law of the ϵ_i's, provided the mean is zero and the variance σ^2 exists. If the distribution is normal, the following additional results follow (Cramér, 1946, Chapters 32–34, 37; Hald, 1952*a*, Chapter 20).

The estimates c_r, w, $\hat{\eta}_i$ have normal distributions, which are completely determined by their means and by their variances and covariances. The quantity Q_0/σ^2 has the chi-square distribution in $n-k$ degrees of freedom (d.f.) and is independent of w, c_r, $\hat{\eta}_i$. The ratio $(w-\omega)/s_w$, where s_w is the estimate of σ_w obtained by replacing σ by s in (4-11), has Student's t-distribution in $n-k$ d.f. These facts can serve as a basis for significance tests and confidence-limit calculations. Furthermore, the best linear estimate has minimum variance not only among all *linear* unbiased estimates (2-3), but among all *regular* unbiased estimates (Cramér, 1946, p. 481).

5. ORTHOGONAL FUNCTIONS

Definition

The formulas of Section 4 become simpler if the functions u_{0i}, u_{1i}, $\cdots$ of i satisfy the condition

$$\sum_i u_{ri}u_{si} = 0 \quad \text{for} \quad r \neq s. \tag{5-1}$$

They are then said to be mutually orthogonal with respect to the points x_1, x_2, $\cdots$, x_n.

Expansion Theorem

Any n mutually orthogonal functions u_{0i}, u_{1i}, $\cdots$, $u_{(n-1)i}$ are linearly independent: that is, no relation

$$C_0u_{0i} + C_1u_{1i} + \cdots + C_{n-1}u_{(n-1)i} = 0 \tag{5-2}$$

can hold identically in i, except the trivial one with $C_0 = C_1 = \cdots = C_{n-1} = 0$. (To prove that C_s must be zero, multiply (5-2) by u_{si}, sum over i, and use (5-1).) But any $n+1$ functions of n points must be linearly dependent; therefore an arbitrary function g_i of i can be expressed in the form

$$g_i = \sum_{r=0}^{n-1} c_r u_{ri}. \tag{5-3}$$

To determine the c_r's, multiply (5-3) by u_{si}, sum over i, and use (5-1). This gives (with a change of the summation index)

$$c_r = (1/S_r) \sum_i u_{ri}g_i, \tag{5-4}$$

with

$$S_r = \sum_i u_{ri}^2. \tag{5-5}$$

Statistical Application

Now return to the least-squares problem of Section 4, and suppose that the k functions u_{0i}, u_{1i}, $\cdots$, $u_{(k-1)i}$ are orthogonal. By (4-9), (5-1), and (5-5), $\alpha_{rs} = S_r\delta_{rs}$, where $\delta_{rr} = 1$, $\delta_{rs} = 0$ for $s \neq r$. The matrix (α_{rs}) is diagonal, and its inverse (β_{rs}) is also diagonal, with elements $\beta_{rs} = \delta_{rs}/S_r$. Therefore (4-8) reduces to (5-4). This means that to fit g_i by least squares to a sum of k terms, $c_0u_{0i} + c_1u_{1i} + \cdots + c_{k-1}u_{(k-1)i}$, we merely omit the last $n-k$ terms in the complete expansion (5-3). The result is the best linear estimate η_i, equation (4-7), of η_i, equation (4-5). The c_r's that are kept are the best linear estimates of the corresponding γ_r's; the c_r's that are omitted are pure error, if the assumed form for η is in fact an adequate approximation ($\gamma_r = 0$ for $r > k-1$).

The variance formula (4-11) becomes, for orthogonal functions,

$$\sigma_w^2 = \sigma^2 \sum_{r=0}^{k-1} v_r^2/S_r. \tag{5-6}$$

The variance of c_r is σ^2/S_r; the quantities $c_r\sqrt{S_r}$ have variance σ^2 and covariance zero. The minimized Q, Q_0, is given by

$$Q_0 = \sum_{r=k}^{n-1} S_r c_r^2, \tag{5-7}$$

from which (4-12) follows directly. For practical calculation, (5-7) can be put into a more convenient form by use of the relation

$$\sum_i g_i^2 = \sum_{r=0}^{n-1} S_r c_r^2. \tag{5-8}$$

Subtraction of (5-8) from (5-7) gives

$$Q_0 = \sum_i g_i^2 - \sum_{r=0}^{k-1} S_r c_r^2. \tag{5-9}$$

TABLE I

SECOND DERIVATIVES, AT CENTRAL POINT ($x=0$), OF ORTHOGONAL POLYNOMIALS $\xi_r'(x)$ FOR ODD NUMBERS (n) OF POINTS: $D^2\xi_r'(0)=N_2/D_2$.

$D^2\xi_r'(0)=N_2/D_2$

n	r	N_2	D_2
3	2	+6	1
5	2	+2	1
	4	−155	6
7	2	+2	1
	4	−67	6
	6	+1519	15
9	2	+6	1
	4	−115	6
	6	+757	15
	8	−327697	840
11	2	+2	1
	4	−25	6
	6	+941	15
	8	−178993	840
	10	+9440387	6300
13	2	+2	1
	4	−247	6
	6	+1946	45
	8	−70655	504
	10	+5502187	6300
	12	−1197748877	207900
15	2	+6	1
	4	−1655	6
	6	+7147	45
	8	−1267271	2520
	10	+11323661	3150
	12	−732999677	207900
	14	+209953547513	9459450

If tables of the orthogonal functions are available, the procedure for estimating the γ_r's and deciding how many terms to keep is as follows (see Section 6 for an illustration). Compute $\sum_i g_i^2$. For each value of r ($=0, 1, \cdots$), compute $h_r = \sum_i u_{ri} g_i$, $c_r = h_r/S_r$, $S_r c_r^2 = h_r c_r$, Q_{0r}, and $s_r^2 = Q_{0r}/(n-r-1)$; the formula for Q_{0r} is $Q_{00} = \sum_i g_i^2 - S_0 c_0^2$, $Q_{0r} = Q_{0(r-1)} - S_r c_r^2$ for $r > 0$. The last Q_{0r}, $Q_{0(n-1)}$, should be zero except for rounding error. Inspect the $S_r c_r^2$ column; decide how many of the quantities $S_r c_r^2$, from the bottom of the table up, can reasonably be considered to be the squares of uncorrelated random variables of mean zero and of common variance. Classify these terms as error, and drop them. In deciding how many terms to keep, watch also the s_r^2 column: its entries should be constant, except for statistical fluctuations, from the bottom up to *and including* the last row retained. The entry in this row is an estimate of σ^2 (but see further discussion in Section 6, *Estimates of Variance*).

Consequences of Normality

So far, it has not been required that the distributions of the ϵ_i's be normal. If they are normal, the following additional results are obtained. The c_r's are independent normal random variables, and the sum of any ν of the quantities $S_r c_r^2/\sigma^2$ with $r \leqq k$ has the chi-square distribution in ν d.f. An estimate s^2 of σ^2 can be found by averaging ν quantities $S_r c_r^2 (r \geqq k)$. If s'^2 and s''^2 are two such estimates, mutually independent and based on ν' and ν'' d.f. respectively, the ratio s'^2/s''^2 has the F distribution in ν' numerator d.f. and ν'' denominator d.f. The F test may therefore be used to compare an earlier group of terms with a later, as a test of the hypothesis that all are pure error. Or an individual c_r may be tested against a group of ν later ones by use of the t test.

Tabulated Orthogonal Polynomials

For a polynomial fit, the functions u_r of the conventional least-squares theory are $1, x, x^2, \cdots, x^r, \cdots$. The corresponding orthogonal functions are polynomials of degrees $0, 1, 2, \cdots, r, \cdots$. For uniformly spaced points at interval 1, there are extensive tables of orthogonal polynomials; see especially Anderson and Houseman (1942), Birge (1947), Fisher and Yates (1949, Table XXIII), and DeLury (1950). All these authors tabulate the same functions, and all but Birge use Fisher's notation $\xi'_r(x)$ to identify them; Birge uses the notation V_r. The functions tabulated by Milne (1949, p. 375–381) in some cases differ from $\xi'_r(x)$ by a constant factor. Of the tables just mentioned, only DeLury's give the polynomials of degrees $6 \leqq r \leqq n-1$ when $n > 6$. Other references are given by Fletcher, Miller, and Rosenhead (1946, p. 363–364).

Other Orthogonal Functions

For special arrays of points, or for functions other than polynomials, special tables must usually be calculated. Any set of n linearly independent functions U_r can be replaced by a set of orthogonal functions u_r by the following method.

Compute in succession

$$\left.\begin{aligned} u_{0i} &= A_0 U_{0i}, \\ u_{1i} &= A_1[U_{1i} - \tau_{10}u_{0i}], \\ u_{2i} &= A_2[U_{2i} - (\tau_{20}u_{0i} + \tau_{21}u_{1i})], \cdots, \end{aligned}\right\} \tag{5-10}$$

where

$$\tau_{rs} = (1/S_s)\sum_i U_{ri}u_{si}; \tag{5-11}$$

the A_r's are arbitrary. The rth step consists in removing from U_{r-1} the part of it that can be expressed as a linear combination of u's already computed; what is left is orthogonal to these u's.

The trigonometric functions used in practical Fourier analysis (Whittaker and Robinson, 1944) are orthogonal. The expansion (5-3) is a generalization of Fourier analysis. The orthogonal polynomials of degrees 0, 1, 2, $\cdots$ have respectively 0, 1, 2, $\cdots$ zeros in the measurement interval; as functions of x in this interval, they resemble waves of successively shorter wave-length.

TABLE 2

FOURTH DERIVATIVES, AT CENTRAL POINT (x=0), OF ORTHOGONAL POLYNOMIALS $\xi_r'(x)$ FOR ODD NUMBERS (n) OF POINTS: $D^4\xi_r'(0)=N_4/D_4$.

$D^4\xi_r'(0)=N_4/D_4$

n	r	N_4	D_4
5	4	+70	1
7	4	+14	1
	6	−406	1
9	4	+14	1
	6	−106	1
	8	+14971	8
11	4	+2	1
	6	−83	1
	8	+13937	24
	10	−30228913	3780
13	4	+14	1
	6	−119	3
	8	+30481	120
	10	−10605569	3780
	12	+535302833	16200
15	4	+70	1
	6	−322	3
	8	+15761	24
	10	−7551674	945
	12	+206035961	16200
	14	−16736950313	124740

TABLE 3

SIXTH DERIVATIVES, AT CENTRAL POINT ($x=0$), OF ORTHOGONAL POLYNOMIALS $\xi_r'(x)$ FOR ODD NUMBERS (n) OF POINTS: $D^6\xi_r'(0)=N_6/D_6$.

$D^6\xi_r'(0)=N_6/D_6$

n	r	N_6	D_6
7	6	+924	1
9	6	+132	1
	8	−13299	2
11	6	+66	1
	8	−2431	2
	10	+2101957	60
13	6	+22	1
	8	−715	2
	10	+457847	60
	12	−354443999	2160
15	6	+44	1
	8	−1339	2
	10	+911027	60
	12	−88136279	2160
	14	+5483082947	7560

Derivatives

In the application to gravity analysis, the quantity of ultimate interest is of the form (4-6). If $\omega=\eta''(0)$, for instance, then $v_r=u_r''(0)$; and the estimate of ω is

$$w = \hat{\eta}''(0) = \sum_{r=0}^{k-1} c_r u_r''(0). \tag{5-12}$$

This formula is not directly useful unless tables of $u_r''(0)$ are available. Derivatives of orthogonal polynomials at uniformly spaced data points can be calculated from tables of the polynomials themselves by standard methods of numerical differentiation (Whittaker and Robinson, 1944; Milne, 1949); the formulas are exact if all non-vanishing differences are kept.

Tables of all the derivatives at all the n points for all values of r, for n odd and $\leqq 15$, have been deposited in the Unpublished Mathematical Tables file of *Mathematical Tables and Other Aids to Computation* (Brown and Dempsey, 1950). Abridged tables are presented here (Tables 1–3);[1] they give only the second, fourth, and sixth derivatives at the central point. Most of the values were calculated by Mr. Carl W. Dempsey of the Sun Physical Laboratory. The derivatives tabulated are derivatives of the polynomials $\xi'_r(x)$ of Fisher and Yates, Anderson and Houseman, and DeLury, or of the polynomials V_r of Birge.

[1] Permanently useful tables are numbered 1, 2, · · · and are assembled at the end of this article. Tables useful only in the discussion of the specific numerical examples of Section 6 are numbered 6-1, 6-2, · · · and are placed near the corresponding parts of the discussion.

Solution of an Estimation Problem

Consider again the illustrative problem of Section 3: to estimate $\eta''(0)$ from $g(0)$, $g(+1)$, etc. If we have tables of the orthogonal polynomials and of their derivatives, we can find the coefficients a_i as follows. With a third-degree polynomial fit, formula (5-12) reduces to $\hat{\eta}''(0) = c_2 u_2''(0)$; then (5-4) gives

$$w = \hat{\eta}''(0) = u_2''(0) \sum_i u_{2i} g_i / S_2 = \sum_i a_i g_i, \tag{5-13}$$

with

$$a_i = u_{2i} \cdot u_2''(0)/S_2. \tag{5-14}$$

The variance of w is, by (5-6),

$$\sigma_w^2 = \sigma^2 [u_2''(0)]^2 / S_2. \tag{5-15}$$

For 5 points, $x_i = (-2, -1, 0, 1, 2)$, standard tables give $u_{2i} = \xi'_2(x_i) = (2, -1, -2, -1, 2)$, $S_2 = 14$; Table 1 gives $u_2''(0) = 2$. Hence $7a_i = (2, -1, -2, -1, 2)$, $\sigma_w^2/\sigma^2 = 2/7$. For 7 points, $x_i = (-3, -2, -1, 0, 1, 2, 3)$, $u_{2i} = \xi'_2(x_i) = (5, 0, -3, -4, -3, 0, 5)$, $S_2 = 84$, $u_2''(0) = 2$. Hence $42a_i = (5, 0, -3, -4, -3, 0, 5)$, $\sigma_w^2/\sigma^2 = 1/21$. These results are the same as those of Section 3.

The method applies to any number of points, degree of polynomial, and order of derivative, within the range of the tables.

6. NUMERICAL EXAMPLES

Synopsis

The following examples are synthetic. Each was made up by adding to a known function η_i a set of independent random "errors" ϵ_i from a normal population of zero mean and known variance. The "errors" were taken from a table of normal random deviates (Wold, 1948). In each example, the object is to decide the proper polynomial degree and to estimate $\eta''(0)$.

Each example will be analyzed in three steps. First, those conclusions will be drawn that are not dependent on normality of the error distribution. Second,

TABLE 4

ORTHOGONAL POLYNOMIALS $\xi_r'(x)$ FOR 7 POINTS

NOTE: $\xi_0'(x) = 1$; $\xi_1'(x) = x$; $\xi_r'(-x) = (-)^r \xi_r'(x)$

x \ r	2	3	4	5	6
0	−4	0	+6	0	−20
1	−3	−1	+1	+5	+15
2	0	−1	−7	−4	− 6
3	+5	+1	+3	+1	+ 1

r	S_r
0	7
1	28
2	84
3	6
4	154
5	84
6	924

TABLE 5

ORTHOGONAL POLYNOMIALS $\xi_r'(x)$ FOR 13 POINTS

NOTE: $\xi_0'(x)=1$; $\xi_1'(x)=x$; $\xi_r'(-x)=(-)^r\xi_r'(x)$

x \ r	2	3	4	5	6	7	8	9	10	11	12
0	−14	0	+84	0	−40	0	+70	0	−252	0	+924
1	−13	− 4	+64	+20	−20	−100	+10	+30	+ 78	−132	−792
2	−10	− 7	+11	+26	+22	− 65	−71	− 6	+210	+165	+495
3	− 5	− 8	−54	+11	+43	+ 75	−19	−31	−285	−110	−220
4	+ 2	− 6	−96	−18	+ 8	+103	+89	+32	+166	+ 44	+ 66
5	+11	0	−66	−33	−55	−121	−55	−13	− 49	− 10	− 12
6	+22	+11	+99	+22	+22	+ 33	+11	+ 2	+ 6	+ 1	+ 1

r	S_r
0	13
1	182
2	2002
3	572
4	68068
5	6188
6	14212
7	92378
8	38038
9	6188
10	386308
11	117572
12	2704156

those additional conclusions will be drawn that are justified if the distribution is normal. Third, the conclusions will be examined on the basis of the known η_i's and ϵ_i's. The third step is possible only in a synthetic problem. In an actual problem, the first step is always possible and the second usually so.

Tables 6-1 and 6-2[2] give the sets of "data" for examples 1–4. Each consists of values of g_i at 7 or at 13 uniformly spaced points. In each, the unit of x is taken

TABLE 6-1

ILLUSTRATIVE DATA (SYNTHETIC): 7 POINTS

x	g		
	Example 1	Example 2	Example 3
−3	0.01916	0.01992	0.02316
−2	0.02433	0.02619	0.04065
−1	0.03301	0.03212	0.06382
0	0.03821	0.03636	0.09522
1	0.03905	0.04094	0.11393
2	0.03852	0.03644	0.09699
3	0.03174	0.03129	0.06301

[2] See footnote 1 (p. 818).

TABLE 6-2

ILLUSTRATIVE DATA (SYNTHETIC): 13 POINTS

x	g
	Example 4
−6	0.02316
−5	0.03151
−4	0.04065
−3	0.04976
−2	0.06382
−1	0.07914
0	0.09522
1	0.10750
2	0.11393
3	0.10762
4	0.09699
5	0.07877
6	0.06301

so that the interval is 1. For reference, Table 4 gives the orthogonal polynomials for 7 points, and Table 5 for 13.

Example 1 (7 Points)

Normality Not Assumed.—Table 6-3 gives the orthogonal-polynomial analysis. From the columns headed $S_r c_r^2$ and s_r^2, one can make the reasonable inference that σ^2 is of order of magnitude 10^{-6}, that the terms $r \leqq 2$ are significant, and that the terms $r \geqq 4$ are mostly error. The term $r = 3$ is doubtful. A doubtful term, if

TABLE 6-3

ORTHOGONAL-POLYNOMIAL ANALYSIS OF EXAMPLE 1

r	$h_r = \sum_i \xi_{ri}' g_i$	$c_r = h_r / S_r$	$\sum_i g_i^2 = .00752484$		$n-r-1$	s_r^2
			$S_r c_r^2 = h_r c_r$	Q_{0r}		
0	+.22402	+.03200286	.00716928	.00035556	6	.00005926
1	+.07216	+.00257714	.00018597	.00016959	5	.00003392
2	−.11452	−.00136333	.00015613	.00001346	4	.00000337
3	−.00765	−.00127500	.00000975	.00000371	3	.00000124
4	+.01407	+.00009136	.00000129	.00000242	2	.00000121
5	−.01398	−.00016643	.00000233	.00000009	1	.00000009
6	−.00950	−.00001028	.00000010	−.00000001	0	—

kept, costs more in labor than it yields in information; we therefore drop the term $r = 3$. Then our estimate of ω is $w = c_2 u_2''(0) = 2c_2 = -0.00273$. The estimated standard deviation of each g_i and of each $c_r \sqrt{S_r}$ is $s = s_2 = \sqrt{(3.37 \times 10^{-6})} = 0.001836$. The estimated standard deviation of w is $s_w = 2s/\sqrt{S_2} = 0.0004006$. The estimates s and s_w are based on 4 d.f.

Normality Assumed.—If the error distribution is normal, the doubtful term $r = 3$ can be tested for significance against the variance estimate $s_3^2 = 1.24 \times 10^{-6}$ based on 3 d.f. If $S_3 c_3^2 = 9.75 \times 10^{-6}$ is pure error, then $F = S_3 c_3^2 / s_3^2 = 7.86$ is drawn from a population that has the F distribution in 1 and 3 d.f. The value of F

that is exceeded with probability 5% is $F_{5\%}=10.13$ (Fisher and Yates, 1949, Table V). Since the observed F is less than this, c_3 is not significant at the 5% level. This gives us a further argument for dropping the term $r=3$.

Normality of the distribution also enables us to calculate confidence limits for ω. The ratio $(w-\omega)/s_w$ has Student's t distribution in 4 d.f. The value of $|t|$ that is exceeded with probability 5% is $t_{5\%}=2.776$ (Fisher and Yates, 1949, Table III). The statement "$-t_{5\%}<(w-\omega)/s_w<t_{5\%}$," if made consistently in many problems, will therefore be true in 95% of all cases. The statement can be rephrased: "ω lies in the interval $w\pm t_{5\%}s_w$"; in the present problem, the interval is -0.00273 ± 0.00111, or -0.00384 to -0.00162. These are the "95% confidence limits" for ω: the statement that ω lies in this interval is based on a rule that guarantees 95% truths and 5% falsehoods.

Examination of Conclusions.—The η of this example is the vertical field intensity of a point mass at depth $z=5$ beneath the point $x=1$: $\eta=z/r^3$, $r^2=(x-1)^2+z^2$. The ϵ_i's were obtained by reading entries from the table of random deviates and multiplying by a constant factor. The value of $\eta''(0)$ is -0.00351, which lies within the calculated confidence limits. However, this apparently satisfactory result needs further examination.

The function η is not actually a polynomial. The question therefore arises: is a polynomial approximation adequate for calculating $\eta''(0)$? We can answer this question by calculating $\eta''(0)$ with the formulas of numerical calculus, which are based on polynomial interpolation. Bickley's 7-point formula (Southwell, 1946, p. 232) gives $\eta''(0)=-0.0034971$, as against -0.0035148 by direct evaluation of $d(z/r^3)/dx$. Therefore a polynomial approximation gives a good value of $\eta''(0)$ (good to within 0.5%) when there is no experimental error.

But under the actual conditions of the example, the terms $r>2$ were so hidden by experimental error that they could not be evaluated. This means that the omitted terms were negligibly small in η; but they are not necessarily small in $\eta''(0)$, for differentiation emphasizes high-degree terms. A second-degree polynomial may introduce a trivial approximation error in η and a serious one in η''. This possibility is not considered in the David-Neyman theory, which treats formulas (4–5) and (4–6) as exact.

To test this idea, we can expand the *exact* function η in orthogonal polynomials and drop the terms after $r=2$. The resulting polynomial is $\eta_2=\gamma_0u_0(x)+\gamma_1u_1(x)+\gamma_2u_2(x)$, and its second derivative at $x=0$ is $\eta_2''(0)=2\gamma_2=-0.00266$. This is the quantity of which w is an unbiased estimate; as an estimate of $\eta''(0)$, w is biased by an amount $-0.00266+0.00351=+0.00085$. It happens that both $\eta''(0)$ and $\eta_2''(0)$ fall within the 95% confidence limits for ω, but $\eta_2''(0)$ is closer to the estimate w.

Estimation of the bias must usually be based on general knowledge of the class of f eld being studied; this is not primarily a statistical problem. The confidence limits take no account of this kind of bias; they allow only for random error.

In this example there is no possibility of evaluating a *fourth* derivative. If we

wish to estimate a fourth derivative, we must get new data in the same region: either more precise data, or many more data of the same precision.

Example 2 (7 Points)

Normality Not Assumed.—Table 6-4 gives the orthogonal-polynomial analysis. As before, the term $r=3$ is doubtful and the later terms are evidently mostly error. By omitting terms $r\geqq 3$ we get $w=-0.00259$, $s=s_2=0.001921$, $s_w=0.0004192$ (4 d.f.).

Normality Assumed.—If the distribution is normal, the test of the doubtful term $r=3$ gives $F=S_3c_3^2/s_3^2=6.10$ (1 and 3 d.f.), not significant at the 5% level. The 95% confidence limits for ω are -0.00259 ± 0.00116, or -0.00375 and -0.00143.

TABLE 6-4

ORTHOGONAL-POLYNOMIAL ANALYSIS OF EXAMPLE 2

r	$h_r=\sum_i \xi_{ri}' g_i$	$c_r=h_r/S_r$	$\sum_i g_i^2=.00741949$		$n-r-1$	s_r^2
			$S_rc_r^2=h_rc_r$	Q_{0r}		
0	+.22326	+.03189429	.00712072	.00029877	6	.00004980
1	+.06343	+.00226536	.00014369	.00015508	5	.00003012
2	−.10857	−.00129250	.00014033	.00001475	4	.00000369
3	−.00770	−.00128333	.00000988	.00000487	3	.00000162
4	+.00644	+.00004182	.00000027	.00000460	2	.00000230
5	+.01447	+.00017226	.00000249	.00000211	1	.00000211
6	+.04413	+.00004776	.00000211	.00000000	0	—

Examination of Conclusions.—The function η of this example is the third-degree polynomial approximation to the η of example 1, *viz.*, $\gamma_0u_0+\gamma_1u_1+\gamma_2u_2+\gamma_3u_3$. The term in u_3 does not contribute to $\eta''(0)$, which therefore is -0.00266. It falls well within the 95% confidence limits.

In this example, where $\eta(x)$ has been artificially constructed to be exactly a polynomial, w is an unbiased estimate of $\eta''(0)$; in example 1, w as an estimate of $\eta''(0)$ was subject to a bias $+0.00085$. Physically this has the following meaning. If the measurements were to be repeated many times in a place where the true intensity was the $\eta(x)$ of the present example, the average of the estimates w from the various sets of measurements would almost certainly lie close to $\eta''(0)$; in a place where the true intensity was the $\eta(x)$ of example 1, this average would almost certainly differ from $\eta''(0)$ by about $+0.00085$. Example 1, of course, is more representative of actual field data.

Example 3 (7 points)

Normality Not Assumed.—Table 6-5 gives the orthogonal-polynomial analysis. Except from $r=4$ to $r=5$, there is a steady decrease of $S_rc_r^2$. Such a steady decrease suggests that in order to fit the function $\eta(x)$ to well within the random error, it is necessary to keep most of the possible polynomial terms; and this leaves too few degrees of freedom for reliable estimation of the random error. The

TABLE 6-5

ORTHOGONAL-POLYNOMIAL ANALYSIS OF EXAMPLE 3

r	$h_r=\sum_i \xi_{ri}' g_i$	$c_r=h_r/S_r$	$\sum_i g_i^2=.0416\,8601$		$n-r-1$	s_r^2
			$S_r c_r^2=h_r c_r$	Q_{0r}		
0	+.49678	+.07096857	.03525577	.00643024	6	.00107171
1	+.28234	+.01008357	.00284700	.00358324	5	.00071665
2	−.48328	−.00575333	.00278047	.00080277	4	.00020069
3	−.06660	−.01110000	.00073926	.00006351	3	.00002117
4	+.04410	+.00028636	.00001263	.00005088	2	.00002544
5	+.06504	+.00077429	.00005036	.00000052	1	.00000052
6	+.02218	+.00002400	.00000053	−.00000001	0	—

only satisfactory remedy is to measure at additional points over the same interval; this will be done in example 4. Meanwhile, we tentatively classify the terms $r>3$ as pure error; then $w=-0.01151$, $s=s_3=0.004601$, $s_w=0.001004$ (3 d.f.).

Normality Assumed.—The cubic term is significant at the 1% level: $F=739.26/21.17=34.92$, $F_{1\%}=34.12$ (1 and 3 d.f.). The 95% confidence limits for ω are -0.01151 ± 0.00319. This result is subject to considerable suspicion of bias.

Examination of Conclusions.—This will be postponed until the related example 4 has been discussed.

Example 4 (13 Points)

The data of example 4 consist of the data of example 3 and of additional data, at the midpoints of the previous intervals. Because the analysis of the original 7 values aroused suspicion that some of the rejected terms might be important, we have returned to the scene and taken some more "measurements." In example 4 we change to a new x-scale, on which the new interval is 1. On this new scale, the previous confidence interval for w becomes -0.002878 ± 0.000798 (one-fourth the previous numerical values).

TABLE 6-6

ORTHOGONAL-POLYNOMIAL ANALYSIS OF EXAMPLE 4

r	$h_r=\sum_i \xi_{ri}' g_i$	$c_r=h_r/S_r$	$\sum_i g_i^2=.0807\,6112$		$n-r-1$	s_r^2
			$S_r c_r^2=h_r c_r$	Q_{0r}		
0	+0.95108	+.07316000	.06958101	.01118011	12	.00093168
1	+1.00292	+.00551055	.00552664	.00565347	11	.00051395
2	−2.93970	−.00146838	.00431660	.00133687	10	.00013369
3	−0.82678	−.00144542	.00119504	.00014183	9	.00001576
4	+1.43908	+.00002114	.00003042	.00011141	8	.00001393
5	+0.80952	+.00013082	.00010590	.00000551	7	.00000079
6	+0.06770	+.00000476	.00000032	.00000519	6	.00000087
7	−0.35404	−.00000383	.00000136	.00000383	5	.00000077
8	+0.05376	+.00000141	.00000008	.00000375	4	.00000094
9	+0.02468	+.00000399	.00000010	.00000365	3	.00000122
10	+0.99822	+.00000258	.00000258	.00000107	2	.00000054
11	+0.20624	+.00000175	.00000036	.00000071	1	.00000071
12	+1.37410	+.00000051	.00000070	.00000001	0	—

Normality Not Assumed.—Table 6-6 gives the orthogonal-polynomial analysis. The last column shows that a fifth-degree polynomial is sufficient. Therefore $w = c_2u_2''(0) + c_4u_4''(0) = 2c_2 - (247/6)c_4 = -0.003807$; $s = s_5 = 0.000889$ (7 d.f.). To find s_w^2, we must multiply s^2 by $(2)^2/S_2 + (247/6)^2/S_4$: see Eq. (5-6). This gives $s_w = 0.000146$ (7 d.f.).

Normality Assumed.—The term $r = 5$ is significant at the 0.1% level ("highly significant"): $F = 10590/79 = 134.1$; $F_{0.1\%} = 29.25$ (1 and 7 d.f.). For 7 d.f., $t_{5\%} = 2.365$; therefore the 95% confidence limits for ω are -0.003807 ± 0.000345. The new estimate does not fall within the old confidence limits, nor the old within the new. This confirms the previous suspicion that the estimate -0.002878 was biased, because of omission of a significant fourth-degree term. The amount of the bias can now be estimated as $-0.002878 + 0.003807 = +0.000929$.

Examination of Conclusions.—In examples 3 and 4, η is the field of a point mass at depth $z = 3$ beneath the point $x = 1$, in the units of example 3: $\eta = z/r^3$, $r^2 = (x-1)^2 + z^2$. The actual value of $\eta''(0)$ is -0.01423 in the units of example 3 and -0.003558 in the units of example 4. This falls within both the old and the new confidence limits. The old estimate, -0.002878, is actually an unbiased estimate of $2\gamma_2/4 = -0.002767$; as an estimate of $\eta''(0) = -0.003558$, it is biased by an amount $-0.002767 + 0.003558 = +0.000791$. This same bias was estimated in the last paragraph as $+0.000929$.

Estimates of Variance

Normality Not Assumed.—In each of the examples, the variance σ^2 was estimated independently from the data of that example. Suppose that the various sets of "measurements" were taken under the same experimental conditions, so that the variance is constant. Then independent estimates $s_{(1)}^2, s_{(2)}^2, \cdots$, based on $\nu_{(1)}, \nu_{(2)}, \cdots$ d.f., can be pooled to get a better estimate, $s^2 = \sum_i \nu_{(i)} s_{(i)}^2/\nu$, based on $\nu = \sum_i \nu_{(i)}$ d.f. Here we have

$$s_{(1)}^2 = 3.37 \times 10^{-6}, \qquad \nu_{(1)} = 4;$$
$$s_{(2)}^2 = 3.69 \times 10^{-6}, \qquad \nu_{(2)} = 4;$$
$$s_{(4)}^2 = 0.79 \times 10^{-6}, \qquad \nu_{(4)} = 7.$$

The estimate $s_{(3)}^2$ from example 3 is not independent of $s_{(4)}^2$ and has therefore been omitted. The pooled estimate is

$$s^2 = 2.25 \times 10^{-6}, \qquad \nu = 15.$$

This estimate includes contributions from the doubtful terms $r = 3$ in examples 1 and 2. In each of these examples, $S_3c_3^2$ is larger than any of the entries below it; it was too small to be useful for estimating $\eta''(0)$, but it may still be too large to be useful for estimating s^2. Such a doubtful term may be of the form $S_3(\gamma_3 + \epsilon_3')^2$, where γ_3 is comparable with the standard deviation of the random error ϵ_3'; then γ_3 is too small to be itself estimated reliably, but too large to be ignored in estimating the error level. Omission of these doubtful terms gives

$$s_{(1)}^2 = 1.24 \times 10^{-6}, \qquad \nu_{(1)} = 3;$$
$$s_{(2)}^2 = 1.62 \times 10^{-6}, \qquad \nu_{(2)} = 3;$$
$$s_{(4)}^2 = 0.79 \times 10^{-6}, \qquad \nu_{(4)} = 7.$$

The pooled estimate is

$$s^2 = 1.08 \times 10^{-6}, \qquad \nu = 13.$$

From the doubtful terms themselves, we get a pooled estimate $s'^2 = \frac{1}{2}(9.75+9.88) \times 10^{-6} = 9.815 \times 10^{-6}$, 2 d.f.; and from the remaining terms of examples 1 and 2 alone, we get a pooled estimate $s''^2 = \frac{1}{2}(1.24+1.62) \times 10^{-6} = 1.430 \times 10^{-6}$, 6 d.f. These numbers strongly suggest that the doubtful terms, if included, would lead to a high estimate of σ^2, and that the estimate 1.08×10^{-6} is better than the estimate 2.25×10^{-6}.

Normality Assumed.—If the error distribution is normal, the suspicion in regard to the doubtful terms can be tested quantitatively. Even though $S_3 c_3^2$ was not significant according to individual F tests in examples 1 and 2, the pooled estimate s'^2 based on the two examples may prove significant when tested against s''^2, because of the increase in sensitivity of the test when the numbers of degrees of freedom are increased. This test gives $F = s'^2/s''^2 = 9.815/1.430 = 6.86$ (2 numerator and 6 denominator d.f.); F is significant at the 5% level ($F_{5\%} = 5.14$), though not at the 1% ($F_{1\%} = 10.92$). The still more sensitive test against 13 d.f. gives $F = 9.815/1.08 = 9.09$ (2 and 13 d.f.); F is significant at the 1% level ($F_{1\%} = 6.70$). Therefore the terms $r = 3$ in examples 1 and 2 should be omitted in estimating σ^2.

Confidence limits for σ^2 can now be calculated. When s^2 is based on ν d.f., $\nu s^2/\sigma^2$ has the χ^2 distribution in ν d.f. Let χ_1^2 and χ_2^2 be the values such that $\chi^2 < \chi_1^2$ with probability 2.5% and $\chi^2 < \chi_2^2$ with probability 97.5%, so that $\chi_1^2 < \chi^2 < \chi_2^2$ with probability 95%. Then the symmetrical upper and lower 95% confidence limits for σ^2 are $\nu s^2/\chi_1^2$ and $\nu s^2/\chi_2^2$. Here $\nu = 13$, $\chi_1^2 = 5.01$, $\chi_2^2 = 24.7$ (Hald, 1952*b*, Table V or Table VI), and the 95% confidence limits for σ^2 are 2.81×10^{-6} and 0.57×10^{-6}. If the doubtful terms were kept, the figures would be $\nu = 15$, $\chi_1^2 = 6.26$, $\chi_2^2 = 27.5$, 95% confidence limits 5.39×10^{-6} and 1.23×10^{-6}.

Examination of Conclusions.—The population variance of the table of random normal deviates is 1.00; the entries were multiplied by 10^{-3}, therefore the variance σ^2 is 1.00×10^{-6}. The 27 values drawn from the table and used in the examples have a sample variance of 1.10×10^{-6}. Both the population variance and the sample variance fall within the 95% confidence interval calculated by leaving out the doubtful terms, but below the interval calculated by including them. Inclusion of terms that are significantly not pure error will, on the average, bias the estimate s^2 upward; for the expected value of $S_r(\gamma_r + \epsilon_r'')^2$ is $S_r\gamma_r^2 + \sigma^2 > \sigma^2$.

The "errors" were read from Wold's tables as follows: example 1, page 1, column 3; example 2, page 1, column 4; example 3, page 1, column 1; additional values for example 4, page 2, column 1. Values were read from the top of the

column down for x increasing. The reader now has enough information to verify the whole calculation.

Test of Normality

If we had many sets of data like the examples, all taken under the same experimental conditions, we could test the error distribution for normality. So far, we have accumulated 13 quantities $c_r\sqrt{S_r}$) that we have classified as pure error (examples 1 and 2, $r \geqq 4$; example 4, $r \geqq 6$). If we had, say, 100 such quantities, we could test for goodness of fit by the χ^2 method (Cramér, 1946, Chapter 30). This method requires arranging the quantities into groups of known theoretical probabilities, with at least 10 in each group.

General Conclusions

These examples demonstrate that by statistical analysis of the data, it is possible to get: (1) reliable estimates of certain derivatives; (2) estimates of the reliability of these estimates; (3) the information that certain other derivatives cannot be evaluated without more precise or more plentiful data; (4) grounds for suspecting that in certain sets of data the points are too far apart; (5) pooled estimates of the error level in a number of similar experiments. All the conclusions drawn have only statistical validity; but that statistical validity can be described quantitatively.

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GRAVITY INVESTIGATIONS IN THE HOCKLEY SALT DOME, HARRIS COUNTY, TEXAS*

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ABSTRACT

Gravity measurements at the surface, in the shaft, and in the drifts of the United Salt Company's mine at the Hockley salt dome have been analyzed to determine densities of sediments, cap rock, and salt rock.

The curve derived from the gravity changes indicates the presence of lithologic breaks that correspond with the known geology of the shaft. The density values computed from this curve correspond closely with accepted values for near-surface clastic sediments, limestone, gypsum rock, anhydrite rock, and salt rock.

INTRODUCTION

It is possible that a gravity meter capable of being lowered into a borehole may be developed in the near future. This prospect prompted several graduate students of the Geology Department of the University of Houston, on the advice of Mr. S. P. Worden of Houston Technical Laboratories, to undertake some gravity measurements inside the Hockley salt dome. The purpose of this survey was to develop computing and interpretation procedures for subsurface gravity measurements and to determine the applications as well as limitations of this exploration technique. In addition, it is hoped that the results of this study will be useful in isolating and solving some of the design and operation problems of remote-controlled borehole gravity meters, as well as in focusing attention on subsurface methods of gravity investigation, particularly for the Gulf Coast.

The gravitational field in the Gulf Coast is distorted by intrusive salt plugs whose gravitational anomalies overlap locally. This condition could cause serious errors in underground vertical-gradient gravity surveys. However, the present work shows that useful data can be obtained in the center of a large complex gravity anomaly.

Hammer (1950) and Rogers (1952) have published the results of two underground vertical gravity surveys, and Smith (1950) has discussed the theoretical aspects of borehole gravity meter surveys.

LOCATION

The Hockley dome is situated 4.5 miles south of the village of Hockley in Harris County, Texas, about 32 air-line miles northwest of Houston. It was selected because of the presence of a deep vertical mine shaft in which gravity

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observations could be made to a depth approximating that of a shallow borehole. The field work was conducted intermittently, beginning in November, 1953 and ending in May, 1954.

GENERAL GEOLOGY

The general geology of the Hockley area is presented to aid the reader in understanding the geophysical information developed by this study. The dome occurs under the southeastern margin of a pronounced topographic feature known as the Williana Terrace, which is underlain by sands and gravels of the Willis formation. The general trend of the terrace margin on the eastern edge of the salt dome is north 55 degrees east, but it extends in a westward direction toward the south edge of the dome. The average elevation of the terrace near the dome is approximately 200 feet above sea level. The dome rises about 50 feet above the plains of the Lissie formation to the southeast.

Hockley, unlike some of the better known Gulf Coast salt domes, (according to Deussen and Lane, 1925) does not have the topographic expression of a dome at the surface. This may be due, in part, to its location. It is situated immediately northwest of the seaward-facing scarp terminating the Williana Terrace. This scarp, which separates the Willis from the Lissie formation, is the most pronounced topographic feature in the area comprising the southeastern margin of the Willis formation. Outcrops of this formation occur on the east, south, and southwest sides of the dome.

Surface Geology

Surface exposures in the area of the Hockley Dome are scarce because of the unconsolidated character and horizontal attitude of the beds at the surface. Near the southeast corner of Robert Hall survey, outcrops of red sand are widespread. These outcrops are probably subsoils derived from the Willis formation.

Exposures of gray sandstone occur toward the southern flank of the dome, in Thomas Coghill survey and near Big Cypress Creek. Although these exposures were assigned to the Miocene or lower Pliocene by Alexander Deussen, their age is still uncertain. These older rocks, above the cap rock, have been brought to the surface by the uplift.

Subsurface Geology

The salt-rock core at Hockley rises to within 1,010 feet of the surface. At its top it is approximately 15,000 ft in diameter along its NW-SE axis and about 10,000 ft along its NE-SW axis.

The cap rock immediately overlying the salt core has a thickness of 995 ft in some areas, tapering toward the edges of the dome. The limits of the cap rock at the 1,000-foot contour are shown by cross marks in Fig. 3.

The bottom layer of the cap is chiefly anhydrite rock, characterized by many joint systems. The horizontal joint planes are smooth but have slickensides. A fine coating of pyrite gives these joint planes a dark appearance.

Gypsum rock overlies the anhydrite-rock layer. The gypsum has been described by H. B. Stenzel (1946), based on information obtained from the now abandonded gypsum mine over the dome. This mine is situated about 800 feet northwest of the salt-mine shaft. The gypsum-rock layer is present only over the central part of the cap rock. It disappears completely toward the edges of the dome and only 18 feet was penetrated in the salt-mine shaft.

The top layer of the cap rock is a limestone which is brecciated and interwoven with veins of calcite. Minor amounts of barite and strontianite occur as concretions, according to Teas (1931, p. 465).

Above the cap rock are unconsolidated deposits of Miocene gravels, sands, and clays. The section penetrated by the mine shaft, as described by L. P. Teas, is described below (compare also Fig. 4):

0– 76 feet—Surface deposits and Miocene and Oligocene sands and clays.
76– 107 feet—Limestone cap rock.
107– 125 feet—Gypsum rock.
125– 800 feet—Anhydrite rock, also anhydrite fragments coated with a green copper mineral.
800– 900 feet—Stratified bands of gray calcareous sandstone in the anhydrite rock, from a fraction of an inch to an inch thick.
900– 973 feet—Anhydrite rock.
About 973 feet—Lens of salt rock, about 10 feet long, 5 feet wide, and 0.9 feet thick.
973–1,010.75 feet—Anhydrite rock.
1,010.75 feet—Top salt rock.

GRAVITY DATA

The underground gravity observations were made with two Worden gravity meters in the United Salt Company's mine shaft at Hockley, Texas. Readings were taken at 10, 20, 30, 40, and 50-foot intervals depending upon the thickness and lithology of the layers traversed.

After experimenting with various methods of supporting and reading the gravity meter in the shaft, Mr. S. P. Worden developed a satisfactory platform to support the meter. The platform was supported by an I-beam, which could be clamped to the framework of the shaft. The supporting platform permitted reading the meter in the elevator bucket without climbing out of the bucket onto the framework.

Elevations in the shaft were measured with a survey chain to the nearest one-tenth of a foot. This accuracy is necessary because of the effect of elevation errors in solving the density equation.

Readings of the two Worden meters were recorded at each station during much of the survey, but during the later part of the work only one meter was used. Base checks were made at least once every hour, and numerous tie stations were reoccupied to obtain accurate data.

Most of the observations in the mine shaft were made by Mr. N. C. Harding of Houston Technical Laboratories (present address, Geophysical Service Inc.). The accuracy of this part of the survey was made possible by his ability to make consistent observations under trying operating conditions in the elevator bucket. These conditions were complicated by salt water draining into the shaft and by the large thermal gradient between the cold winter temperature at the surface

and the high temperature in the mine. Frequent level and calibration checks of the meter assured proper performance of the instrument.

The drift of the field meter and a plot of lunar attractions determined from tidal drift data are shown in Figure 1. These data were furnished by LaCoste-

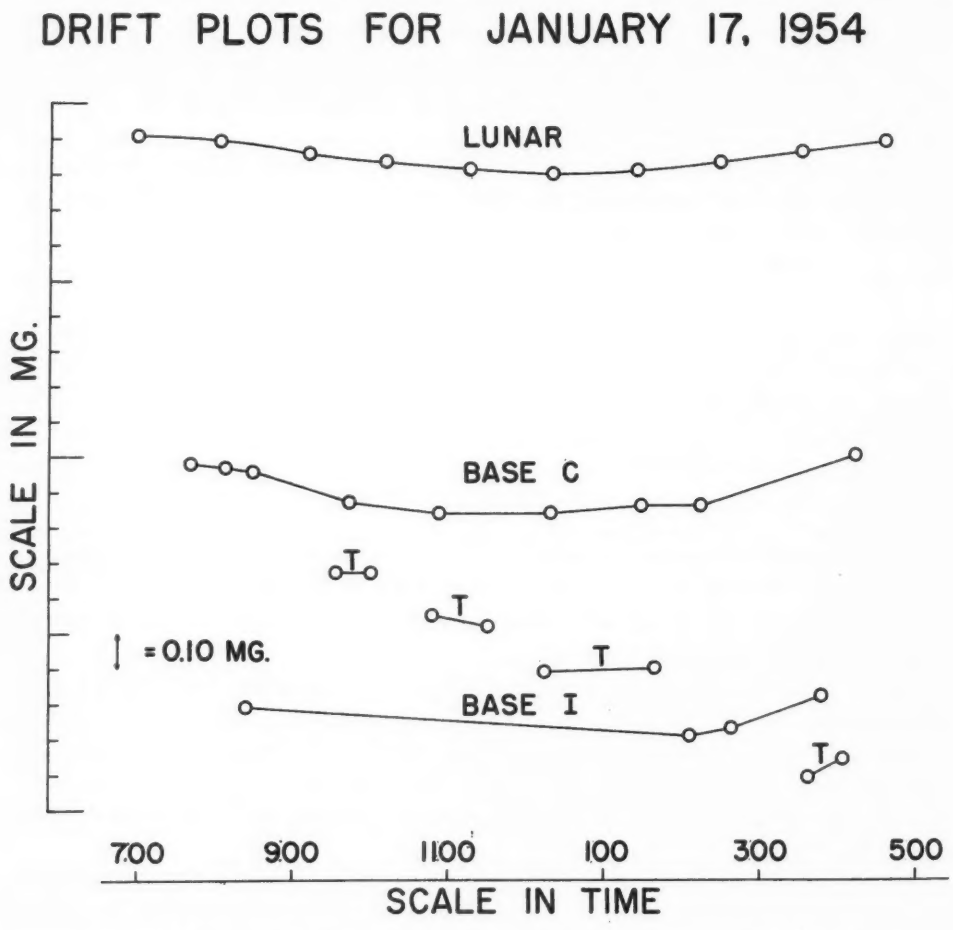

FIG. 1. Comparison of drift curves at base stations with computed lunar drift.

Romberg of Austin, Texas. The differences noted in the two curves may represent a combination of thermal effects and observational errors.

Reduction of Data

The reduction of the surface data was made by standard computing methods. The subsurface data were reduced by methods suggested by Dr. L.L.Nettleton, Dr. S. Hammer, and Mr. N. J. Smith.

The normal vertical gradient, corresponding to the usual free-air correction,

is 0.09406 mg/ft. The effect corresponding to the Bouguer correction is doubled in taking the meter underground because in going down through a given thickness of rock the downward attraction is removed and its upward attraction is added. Therefore, the Bouguer effect beneath the surface of the ground is $2(0.01276\sigma)$ mg/ft. The total gravity effect, in traversing a thickness Δh of a material having a density σ, is:

$$\Delta g = [0.09406 - 0.02552\sigma]\Delta h \tag{1}$$

and the measured vertical gradient in the shaft is:

$$\frac{\Delta g}{\Delta h} = 0.09406 - .02552\sigma, \tag{2}$$

from which the density of the material traversed is given by:

$$\sigma = \frac{0.09406 - \Delta g/\Delta h}{0.02552}. \tag{3}$$

For densities of the order of those of ordinary rocks the first term is much larger than the second, causing a strong positive downward vertical gradient. To remove this steep slope it is convenient to calculate the gradient for approximately the average density of the material traversed. Then this "normal gradient" is subtracted before plotting the depth-gravity curve. The slopes of the resulting "residual" curve then give a measure of the local deviations of the density from the value of the assumed normal density. If the curve slopes upward the density is lower, and if it slopes downward the density is higher than the average density used in removing the normal gradient.

Using the gravity difference from top to bottom of the mine shaft the calculated average density is 2.51. The normal change in gravity was calculated for a density of 2.50 and was then removed from the original observed curve. Therefore values on the "residual" curve are equal to $g_{obs} - g_{calc}$, where

$$g_{calc} = (0.09406 - 0.02552 \times 2.50)\Delta h = 0.03026\Delta h. \tag{4}$$

Assume the slope of the "residual" curve to be $\Delta g/\Delta h$. This ratio is a measure of the difference of the actual density from the value 2.50. In addition, neglect any possible anomalous influence in the vertical gradient. Then the differences in density from the average density used can be computed by the formula

$$\Delta\sigma = -39.20\frac{\Delta g}{\Delta h} \tag{5}$$

and the individual rock density traversed is

$$\sigma = 2.50 - 39.20\frac{\Delta g}{\Delta h}. \tag{6}$$

TABLE I

DENSITY CALCULATIONS FROM MINE SHAFT DATA

	Location in feet	Obs. Δg mg	Normal Δg_n,* mg	$\Delta g - \Delta g_n$ mg	Δg mg	ΔH feet	$\Delta\sigma$ cgs	σ cgs
Surface deposits sandstone and clay	0.0	0.00	0.00	0.00	+0.24	23.1	−0.407	2.09
	23.1	0.94	0.70	+0.24	+0.32	20.0	−0.627	1.87
	43.1	1.86	1.30	+0.56	+0.24	20.0	−0.470	2.03
	63.1	2.71	1.91	+0.80	+0.10	10.5	−0.373	2.13
	73.6	3.13	2.23	+0.90	+0.07	9.6	−0.286	2.21
Limestone cap rock	83.2	3.49	2.52	+0.97	+0.06	13.0	−0.181	2.32
	96.2	3.94	2.91	+1.03	+0.02	10.0	−0.078	2.42
	106.2	4.26	3.21	+1.05	+0.06	9.9	−0.238	2.26
gypsum	116.1	4.62	3.51	+1.11	+0.11	10.0	−0.431	2.07
Anhydrite	126.1	5.04	3.82	+1.22	+0.04	10.1	−0.155	2.35
	136.2	5.38	4.12	+1.26	0.00	20.3	0.000	2.50
	156.5	6.00	4.74	+1.26	−0.03	19.9	+0.059	2.56
	176.4	6.57	5.34	+1.23	−0.03	19.9	+0.059	2.56
	196.3	7.14	5.94	+1.20	−0.06	20.1	+0.017	2.62
	216.4	7.69	6.55	+1.14	−0.03	20.0	+0.059	2.56
	236.4	8.26	7.15	+1.11	−0.19	40.1	+3.186	2.69
	276.5	9.29	8.37	+0.92	−0.16	39.7	+0.158	2.66
	306.2	10.03	9.27	+0.76	−0.26	39.6	+0.257	2.76
	345.8	10.96	10.46	+0.50	−0.34	49.3	+0.270	2.77
	395.1	12.12	11.96	+0.16	−0.40	49.9	+0.314	2.81
	445.0	13.23	13.47	−0.24	−0.40	50.0	+0.314	2.81
	495.0	14.34	14.98	−0.64	−0.40	50.2	+0.312	2.81
	545.2	15.46	16.50	−1.04	−0.51	60.0	+0.333	2.83
	605.2	16.76	18.31	−1.55	−0.44	49.1	+0.351	2.85
	654.3	17.81	19.80	−1.99	−0.48	50.1	+0.376	2.88
	704.4	18.85	21.32	−2.47	−0.48	49.9	+0.377	2.88
	754.3	19.88	22.83	−2.95	−0.49	49.9	+0.385	2.89
Banded anhydrite	804.2	20.90	24.34	−3.44	−0.49	49.7	+0.386	2.89
	853.9	21.91	25.84	−3.93	−0.53	51.1	+0.407	2.91
Anhydrite 1 ft salt	905.0	22.93	27.39	−4.46	−0.25	29.0	+0.338	2.84
	934.0	23.55	28.26	−4.71	−0.31	30.1	+0.403	2.90
	964.1	24.15	29.17	−5.02	−0.25	21.0	+0.466	2.97
Anhydrite rock	985.1	24.54	29.81	−5.27	−0.05	19.0	+0.103	2.60
	994.1	24.76	30.08	−5.32	−0.10	9.9	+0.396	2.90
	1,004.0	24.96	30.38	−5.42	−0.07	10.0	+0.274	2.77
Salt rock	1,014.0	25.19	30.68	−5.49	+0.03	10.1	−0.116	2.38
	1,024.1	25.53	30.99	−5.46	+0.15	10.1	−0.582	1.92
	1,034.2	25.98	31.29	−5.31	+0.07	9.2	−0.298	2.20
	1,043.4	26.33	31.57	−5.24	+0.06	20.6	−0.114	2.39
	1,064.0	27.02	32.20	−5.18	+0.14	20.1	−0.273	2.23
	1,084.1	27.76	32.80	−5.04	+0.33	40.0	−0.323	2.18
	1,124.1	29.31	34.02	−4.71	+0.33	40.0	−0.323	2.18
	1,164.1	30.85	35.23	−4.38	+0.31	40.1	−0.303	2.19
	1,204.2	32.37	36.44	−4.07	+0.36	49.1	−0.287	2.21
	1,253.3	34.21	37.92	−3.71	+0.31	50.3	−0.241	2.26
	1,303.6	36.05	39.45	−3.40	+0.17	29.8	−0.223	2.28
	1,333.4	37.12	40.35	−3.23				

*For assumed normal density of 2.50.

These formulas and methods can be used to compute densities for any other locality. The density computation sheet used for the Hockley data is shown in Table I.

Several conditions may produce errors in these computations. The precision of the density value is dependent upon the accuracy of the gravity and elevation differences relative to the total interval over which they are measured. As pointed out by Hammer (1950), errors may also result from terrain corrections, from an anomalous vertical gradient, from the absolute calibration of the gravity meter, and from effects of the mine openings. Terrain and mine-opening effects are small in the Hockley salt mine except near the top and bottom of the shaft. Therefore, they have been neglected.

Gravity-Density Interpretation

The interpretation of the gravity log is facilitated in this study by the fact that the depths to all the interfaces between rock units, as well as the lithology of each unit, are known. The vertical distribution of the gravity, density, and lithology in the mine shaft are shown in Figure 2 for comparison.

The slope of the gravity curve from the surface to a depth of 76 ft, where the first break is visible, indicates a density of 1.9 to 2.1. This range appears to be reasonable for the density of the unconsolidated sediments on the top of the dome (Dickinson, 1953). The first two observations may include end effects, as well as terrain effects at the top of the shaft, for which corrections have not been applied.

The next segment in the curve, between 76 and 107 ft, indicates a density of 2.1 to 2.4. This part of the curve corresponds to the highly fissured limestone cap rock which forms the top of the dome.

An average density of 2.2 over the next interval, of 107 to 125 ft, correlates with the 18-ft bed of gypsum rock. Detection of this thin bed by the gravity meter illustrates its resolving power for defining density discontinuities in a geologic section.

The interval from 125 to 1,010 ft indicates a density of 2.2 at the top, as well as an almost linear density increase with depth attaining a value of 2.8 at about 340 ft. The latter value persists from 340 ft down to 1,010 ft. This part of the curve corresponds to the anhydrite-rock layer of the cap rock, and the higher densities coincide with accepted values for this material. The increase in density starting at about 340 ft may be due to a gradual decrease of gypsum inclusions in the anhydrite rock from top to bottom but it is probably caused by a local thickening of anhydrite rock, which is indicated by the surface gravity measurements. If the latter explanation is correct, the thickening of the anhydrite which causes a sharp build-up in the surface gravity anomaly would prevent this layer from conforming to a horizontal stratum of infinite extent as called for in the Bouguer formula. The apparent density is a weighted average of the density of the anhydrite and the density, which is lower, of the gypsum, sand, and shale

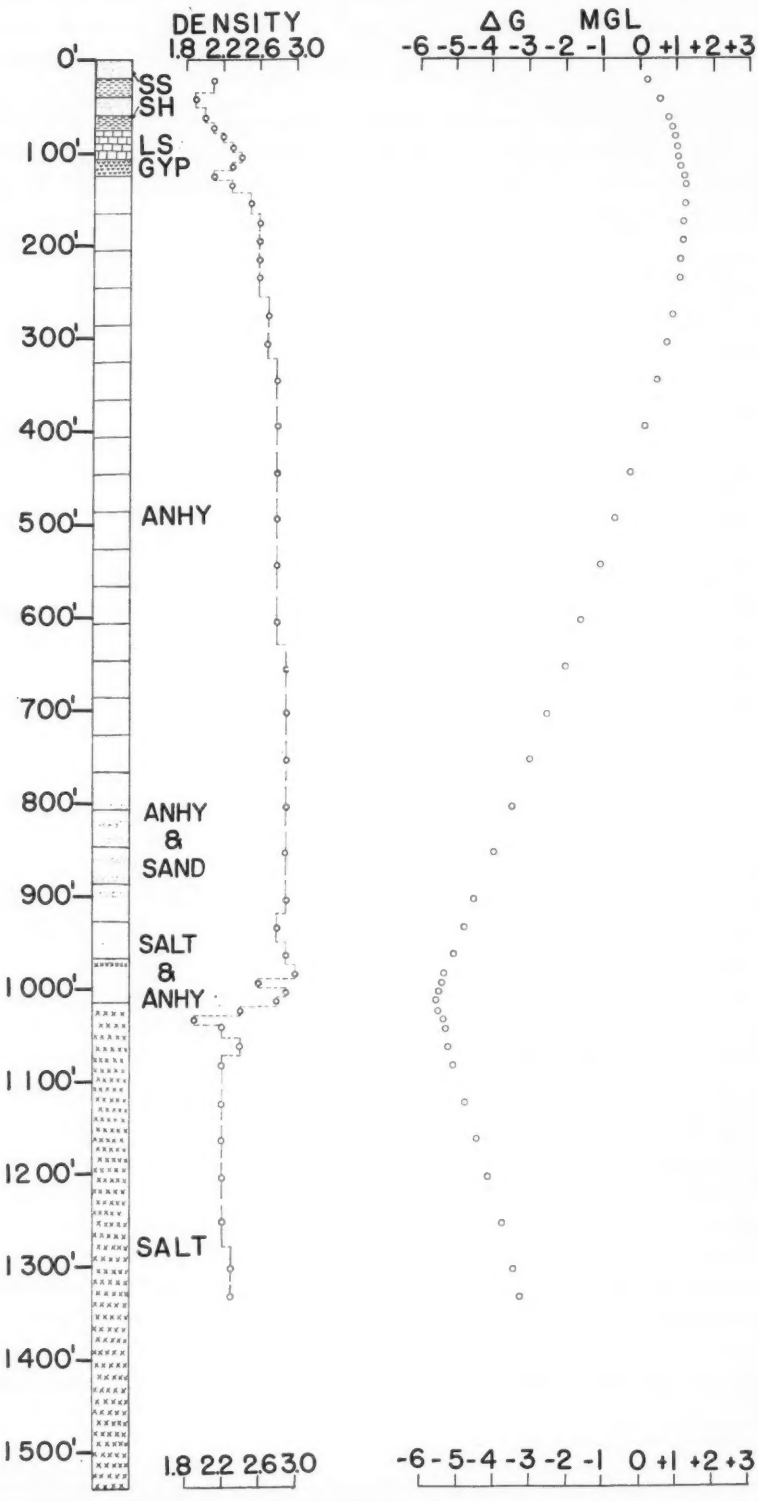

FIG. 2. Comparison of lithology, density, and gravity in Hockley mine shaft. Anhy is anhydrite rock; Gyp, gypsum rock; Ls, limestone; Salt, salt rock; Sh, shale; Ss, sandstone.

which lies outside the build-up. As the lateral extent of the anhydrite incre with depth, the apparent density increases correspondingly. When the anhyd rock is of sufficient areal extent to conform to conditions called for in the Boug formula, the apparent density approaches that of anhydrite.

Salt rock comprises the interval from 1,010 to 1,200 ft. This interval be with the most marked break in the gravity log, indicative of a density of 2.(2.2, which corresponds closely to values found in the literature.

The last two stations at the bottom may be in error because of the large e vation at the bottom of the shaft. Corrections were not made for these stati because the interval was all salt and no appreciable density differences were pected.

In the present investigation density values were not determined from s ples because part of the shaft is lined with concrete. This omission is regrett because Hammer (1950) has determined significant differences between san densities and densities measured by the gravity meter. His samples were rest as well as possible to natural conditions, yet a large range of differences exi between the values obtained by the two methods. To explain these differe all factors that would influence the measurements were evaluated. It was cluded that the differences were due to the samples having been removed f their natural environment, and that the gravity meter was determining the ac in-place bulk densities of the formations. Because samples were not obtai from the mine shaft, Table II was prepared using published density values Gulf Coast rocks. Although the values in the table should not be compa directly with those from Hockley, their range indicates the proper orde magnitude.

SURFACE GRAVITY

The major purpose of the surface gravity survey was to evaluate the l gravity anomaly associated with the dome and to determine if the anon would introduce any error in the free air correction. Each gravity station reoccupied at least once so that confidence could be placed in small anom reflecting changing structural or lithologic conditions in the cap rock. In addi the station spacing was closer than in conventional work so that shallow feat would be measured. Transit plate angles were used in place of magnetic bear to keep the error of poor station locations to a minimum. The surface gra map is shown in Figure 3.

Another objective of the surface survey was to detect any possible sha lateral lithologic variations in the cap rock near the shaft. For example, len of some member of the cap rock having a large density contrast might influ the density values as computed from the subsurface gravity readings. Er would be introduced by the fact that any lens-shaped formations would conform to the concept of horizontal stratification of infinite extent assume the Bouguer formula.

The gravity map shows a typical Gulf Coast salt dome gravity anom

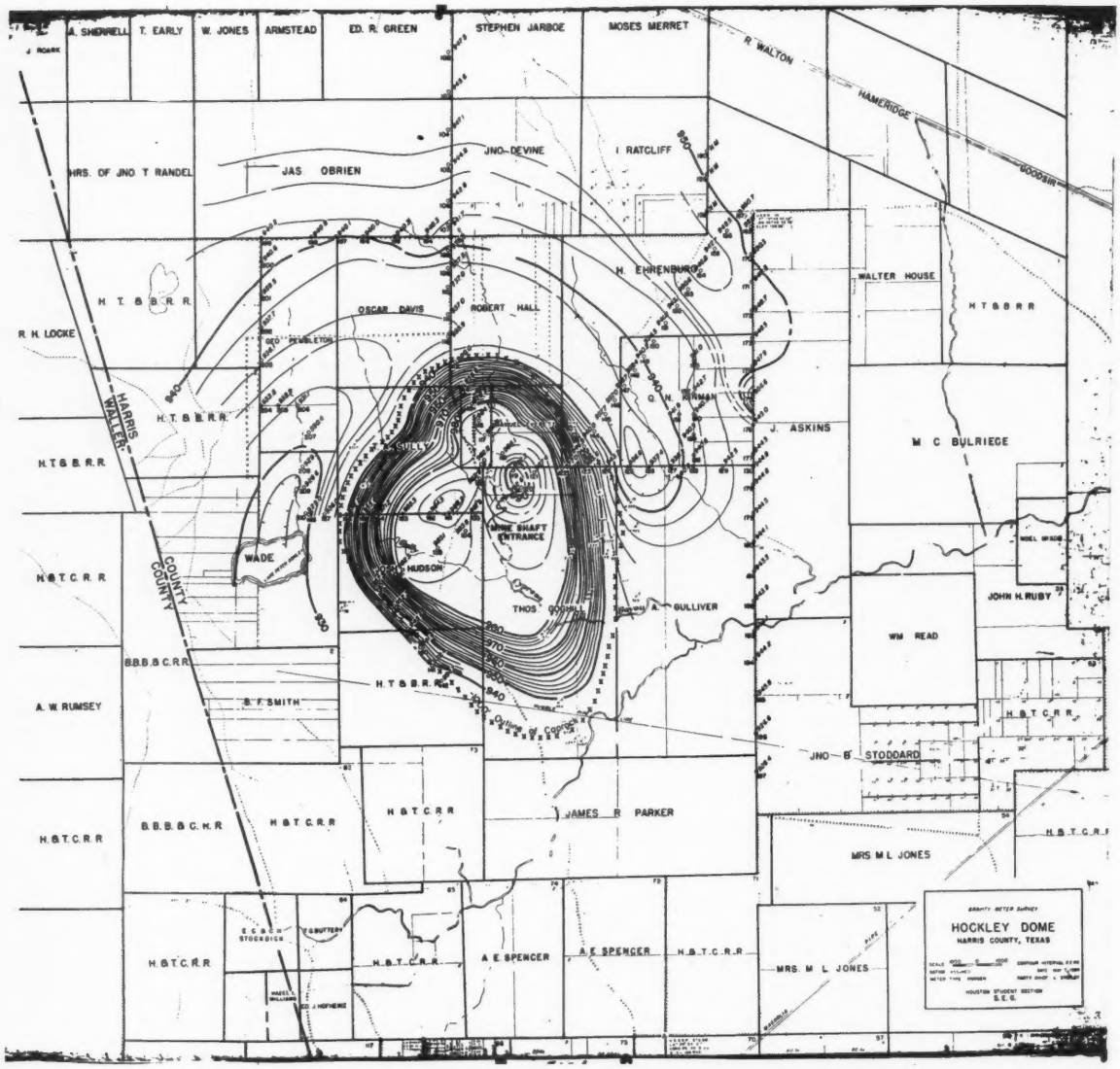

FIG. 3. Surface gravity map of the Hockley area.

The gravity maximum of the cap rock is flanked peripherally by an associated rim minimum caused by salt at depth. Any anomalous effect this feature might exert on the vertical gradient is too small to produce an appreciable error in the calculation.

Near the center of the large maximum is a smaller gravity maximum of 1.3 mg closure, which centers around the mine shaft. Quantitative studies of this smaller gravity maximum suggest that it could be caused by a body at a depth

of about 1,000 ft, but most probably it reflects a local high on the top of the cap rock. This interpretation is substantiated partially by the increase in apparent density with depth of measurement in the dome over the range from 125 to 340 ft.

From the surface gravity and corehole information it is concluded that the remaining part of the dome, which could have an influence on the gravity observations in the mine shaft, is laterally homogeneous and would not contribute any appreciable error.

CONCLUSIONS

The results of this survey substantiate previous theoretical calculations and actual measurements done by others. They indicate the value of additional subsurface gravity work in the Gulf Coast utilizing, for example, remote-controlled meters in deep boreholes.

TABLE II

Published Rock Densities for Gulf Coast Rocks				Computed Rock Densities at Hockley	
Material	Locality	Depth, ft.	Densities	Depth, ft.	Densities
Sand	Gulf Coast		2.18–2.26		
Shale	Gulf Coast	0– 250	1.6 –1.9		
Limestone Cap Rock	Brazoria Co., Texas	1,000–2,000	2.69	76– 107	2.1–2.4
Gypsum	Gulf Coast		2.2 –2.4	107– 125	2.2
Anhydrite	Brazoria Co., Texas	1,000–2,000	2.47–2.93	125– 800	2.2–2.8
Salt	Gulf Coast		2.16–2.22	1,010	2.0–2.2

Knowledge of interval subsurface densities has the same relation to gravity prospecting as a knowledge of velocity values has to seismic prospecting and a knowledge of resistivity values to electrical well logging. Therefore, to obtain the maximum information from gravity surveys, subsurface densities within major lithological intervals must be known. Borehole surveys in the Rocky Mountain and Canadian areas would help to solve the problem of the elevation-correction factor existing in those areas. The information could be obtained in seismic shot holes as suggested by Smith (1950). Calculation of the depth and configuration of a salt dome would be improved by subsurface bulk density data obtained from deep boreholes.

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GEOPHYSICS, VOL. XX, NO. 4 (OCTOBER, 1955), PP. 841–859, 14 FIGS.

SIMULTANEOUS GAMMA RAY AND RESISTANCE LOGGING AS APPLIED TO URANIUM EXPLORATION*

R. A. BRODING† AND BEN F. RUMMERFIELD†

ABSTRACT

The transferring of petroleum exploration thinking and methods to uranium exploration has greatly facilitated the search for radioactive ores. Radioactivity and resistance[1] logs obviate the need and expense of taking continuous cores to locate mineralized zones in shallow core holes. Specialized instrumentation, field equipment, and interpretive techniques are required in applying these logging methods to uranium exploration. Radiometric analysis from logs is possible, but must be carefully controlled, calculated, and qualified. Results are presented of actual uranium exploration in the field.

The impact of atomic energy on world economics makes it necessary to scrutinize the applicability of all geophysical methods to uranium exploration.

INTRODUCTION

Oil companies accustomed to thinking in terms of long-range planning for reserves should encounter little difficulty in widening the scope of their foresight to include atomic energy. This is particularly true in view of the possibility that atomic energy may, in the foreseeable future, replace a portion of the petroleum market as a source of energy for major power installations.

One application of petroleum exploration instrumentation and techniques to uranium exploration is the use of gamma-ray and resistance logging. It is estimated that approximately three million feet of boreholes will be drilled this year in exploration for uranium on the Colorado Plateau alone. To evaluate this footage properly, it is necessary to obtain either continuous cores or radioactivity and resistance logs of the holes. As a matter of economics, it is not only a great deal faster to log the holes than to obtain cores, but it is also from three to four times cheaper.

GEOPHYSICAL PROBLEM

It is becoming increasingly evident that the exploration for uranium is a science, just as is petroleum exploration. The merely random examination of outcrops or terrain does not begin to reveal ore potentialities. It is well known that a mantle of a relatively few inches will completely mask the effect of any underlying radioactive ore body; therefore, the drilling of test holes is essential to evaluate an area. One's first reaction is usually to think in terms of utilizing a Geiger

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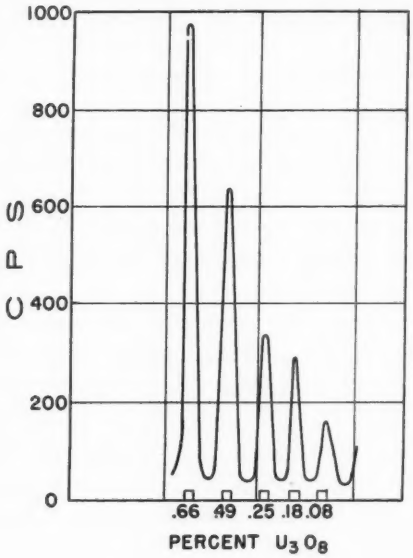
[1] The terminology "resistance logging" is used in preference to the more conventional term "resistivity logging" because the actual measurement made with the described apparatus is a resistance measurement. However, a log of resistivity as made with a multi-electrode probe will have the same merits as a resistance log in this application, provided the measuring electrode spacing is of the order of 6 inches or less.

counter or scintillometer to investigate cuttings from the test holes. Since such an investigation merely indicates the possibility that an ore body has been penetrated, one might consider suspending the probe in the borehole to determine the magnitude of the activity *in situ* and the depth of the source.

If the problem were merely to indicate the presence of an ore body directly as a "yes or no" proposition, it would be a relatively simple matter to solve it by these techniques alone. However, as one becomes familiar with the field, it is realized that the deposition and concentration of uranium ores is complex and depends upon a relatively unknown interrelation of stratigraphy, lithology, and chemical conditions. Therefore, the "yes or no" type of exploration is completely



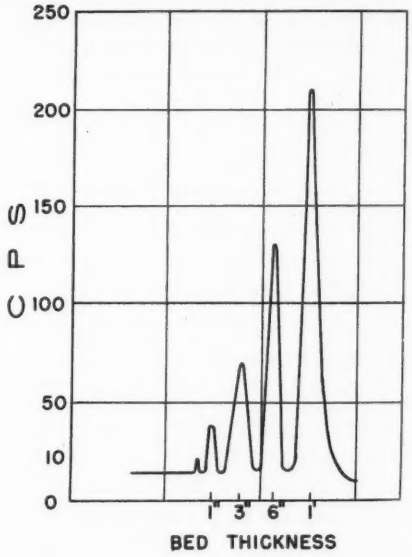


FIG. 1. Response to different concentrations of ores of constant bed thickness.
FIG. 2. Response to beds of various thicknesses with identical concentrations.

inadequate. High calibre instrumentation is required that will yield a continuous log of the natural gamma-ray activity as well as a log that will identify lithology. To meet this requirement, we consider a combination gamma-ray-electrical-resistance log to be the best tool known to date.

Since uranium itself is not a gamma emitter, it is important to note that the measurement of gamma rays cannot be used to detect uranium directly. Fortunately, the uranium series has five daughter elements that are gamma-ray emitters. A gamma-ray detector, therefore, measures the relative proportion of these gamma-emitting elements in the ore, providing that it is in equilibrium. If the ore is in equilibrium, a calibration curve can be drawn which relates counts per second, or milliroentgens per hour, to percent U_3O_8 equivalent. Thus, a radiometric assay can be obtained in the borehole. Such surveys are correct only to

within 15 to 20 percent, but they are still helpful in providing a relative measurement of the ore concentration. Calibration curves must be established for each logging rate, time constant, bed thickness, borehole diameter, and the area involved. Chemical analyses should be run on cores obtained from "hot holes" to evaluate fully the properties of the ore body and, by comparison with the radiometric assay, to establish whether a condition of equilibrium exists. It has been found that conditions of inequilibrium, resulting in excessive radon gas or solution concentrations, can be detected by lack of reproducibility of anomalies in successive logs from the same hole. The possibility that equilibrium does not exist is one of many limitations of radiometric assaying.

Figure 1 illustrates the response of a gamma-ray detector in an artificial test hole to various concentrations of ores with constant bed thickness. A comparison log, shown in Figure 2, illustrates the response in an artificial test hole to ore beds of various thicknesses but with identical concentrations. Calibration runs of this type are the basis for correction curves which are described later.

Experience has taught that uranium-bearing minerals have an affinity for sedimentary deposits where there is a change of facies. That is, lenticular fluvial sandstones that grade into siltstone and mudstone are more favorable for uranium mineralization than are massive clean sandstones. Carbonized fossil plant matter is usually associated with uranium minerals in sedimentary rocks; also, uranium minerals seem to prefer a buff- or light-colored matrix in contrast to red-colored host rocks. Because of these factors, an accurate lithological log is an essential accessory to the gamma-ray log. In some areas, the gamma-ray log gives a fair indication of lithology. However, since this log measures only the amount of natural radioactivity in the rocks and does not necessarily indicate the type of rocks, the gamma-ray log is considered to be a poor lithologic log. Resistance logging is recognized as the best means of obtaining lithologic information, since most rock types are characterized by definite ranges of electrical resistivity. The resistance log, recorded simultaneously with the gamma-ray log, is the ideal combination for uranium exploration.

Through the use of a combination resistance and gamma-ray log, it is possible to construct regional "preference maps" outlining areas in which the uranium prospector is most likely to succeed. For example, erosional channels in the Moenkopi formation are important to delineate, since such channels are often mineralized. Resistance logs can help to locate these channels by identifying the contact of the Shinarump conglomerate which fills them.

Geological marker horizons often can be picked from the resistance logs and sometimes from the gamma-ray logs. For example, in many areas of the Colorado Plateau the Salt Wash or Lower Morrison section can sometimes be identified by characteristic resistivity markers. This is significant, since the Salt Wash has proven to be the most important source to date of uranium ores in this area.

The mineralization along fault zones and the clustering of uranium deposits along the flanks of major uplifts or intrusives indicate the importance of studying

lithology, stratigraphy, and structure in the exploration for uranium. Such structural features as regional dips, synclinal and anticlinal trends, possible channeling, pinchouts, and faulting should be mapped in uranium prospecting just as they are in petroleum exploration. Structural contour, regional trend, isopach, and isolith maps all are useful for this type of study. The similarity of approach, vocabulary, thinking, and philosophy required in the two types of exploration makes it relatively easy for those experienced in oil prospecting to put their experience to advantageous use in the search for uranium.

In many areas, it is feasible to combine petroleum and uranium exploration

FIG. 3. Typical logging operation in conjunction with seismic crew.

with very little additional expense and effort. The logging of seismic shot holes, stratigraphic tests, and core holes is readily accomplished. Admittedly, the control obtained in holes having the spacing required in ordinary seismic surveys can be considered only as reconnaissance when applied to uranium exploration but valuable information can still be obtained from such logging. The major expenditure, that of drilling the hole, already has been made so that the logs have been acquired at little extra cost. No delay is encountered in the operations of the seismic crew, since the logging unit can work between the drills and the shooting crew. Figure 3 illustrates a typical field operation in which the logging unit, mounted on a power wagon, is shown taking a log in a hole while the seismic recording truck is laying out cables preparatory to shooting the next spread.

Recent uranium discoveries suggest that exploration for uranium should not be confined to any one geological or geographical province any more than is exploration for petroleum. The equipment, instrumentation, and personnel used in uranium exploration must be of high calibre, and adequate knowledge and experience are necessary to evaluate the results obtained.

INSTRUMENTATION

A logging instrument has been designed by Century Geophyscial Corporation that allows for the simultaneous logging of natural gamma-ray activity and elec-

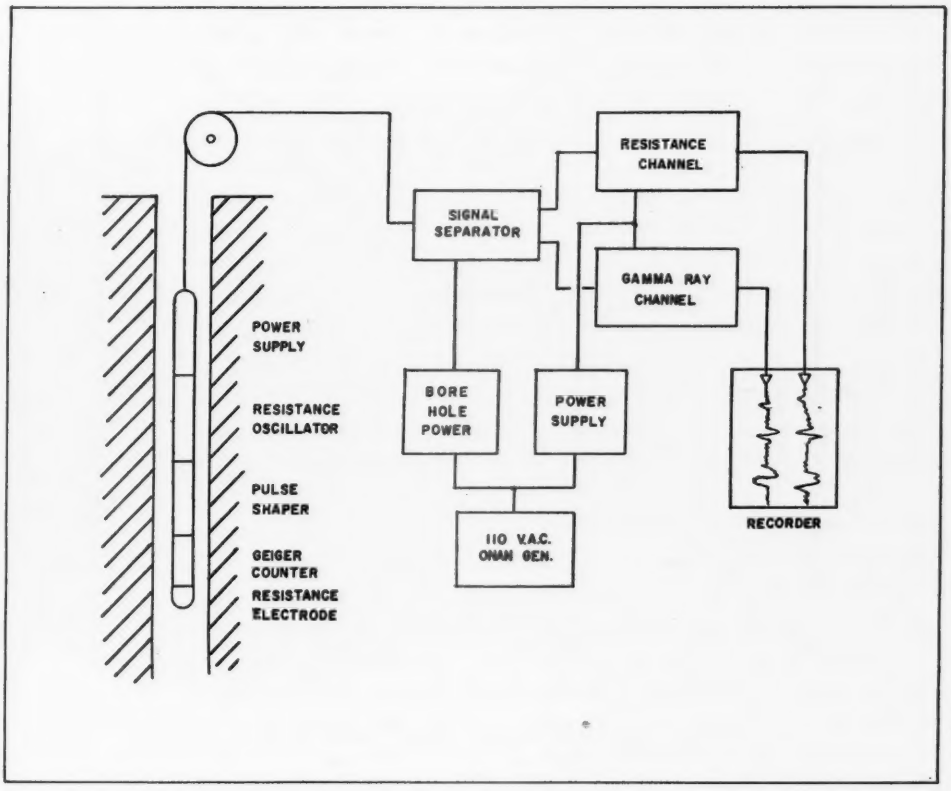


FIG. 4. Block diagram of Gamma-R logging system.

trical resistance of the rock surrounding a bore hole. This instrument, called the Gamma-R Logger, is illustrated schematically in Figure 4.

As only relative values of rock resistance are necessary and as a high degree of vertical resolution is required, a single electrode is used to obtain a resistance measurement. This measurement is telemetered, along with the gamma-ray signal, over a single-conductor logging cable. The circuit is such that leakage require-

ments and the length of cable are not critical. At the surface, the two signals are separated and fed through appropriate amplifiers, pulse shapers, and counting rate meters, and then recorded on a dual Brown recorder. All power is derived from a 115-volt, 60-cycle, gasoline-driven generator. The gamma-ray portion has a full-scale linear calibration from 10 to 10,000 cps in 10 decade steps. Figure 5 shows the relationship between microroentgens per hour and counts per second over the operating range of the instrument, utilizing a Ra^{226} source in air to obtain the data. Six time constants are available, covering the range of 0.5 to 16 seconds. The selection of time constant is dependent upon the counting rate, logging

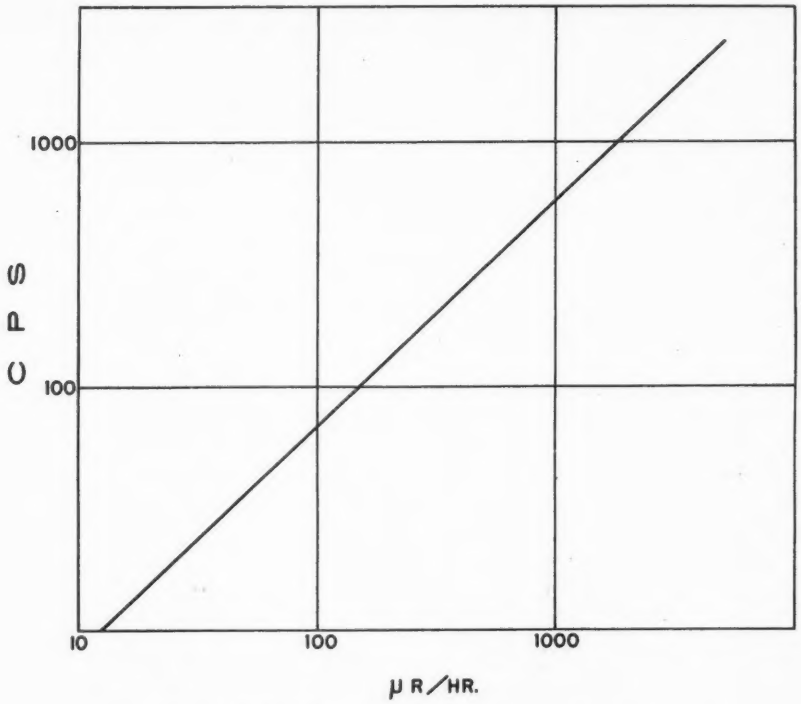


FIG. 5. Calibration curve—Radium^{226} source in air.

speed, and precision of measurement required so that the statistical variations will be within the allowable limits of error.

A profile of typical logs from the Colorado Plateau area is shown in Figure 6. These logs, taken in a series of holes approximately 150 feet apart, illustrate the type of correlations that can be expected between lithology and the resistance log, as well as the correlation and assay of a mineralized zone that is made possible by the gamma-ray log.

Units of this design have been proven in the field to have the required sensitivity and, almost of equal importance, the stability required to withstand the rugged

field, transportation, and temperature conditions inherent in exploration work. A typical installation is shown in Figure 7. A boom arrangement makes it possible to position the logging tool conveniently over the hole. An accessory tripod arrangement also is available to permit the logging of holes that are beyond the reach of the boom arm.

An internal view of the logging truck is shown in Figure 8. A 115-volt, 60-cycle generator, driven by a power takeoff from the truck engine, provides power for an electric motor-driven hoist and the electronic instrumentation. A measuring sheave in the boom assembly provides an accurate measurement of depth and, by selsyn drive, advances the recording chart. Chart speeds of 10, 20, and 50 feet of hole to one inch of chart are used. Normally, 2,000 feet of cable are carried, and hoisting speeds in the range of 2 to 100 feet per minute are available.

The instrumentation is designed for operations to 10,000 feet in depth and temperatures in excess of 200° F. The logging unit is a one-man operation and, because of this fact, a front end winch is used and other safety precautions are taken to insure the operator's being able to "get home" alone. The safety of the operator cannot be stressed too greatly. There is considerable risk in traveling over mountainous terrain with few or no roads as well as in being caught in the extremes of weather often encountered in the remote areas where these units operate. A four-wheel-drive vehicle is considered mandatory.

Figure 9 shows a typical logging operation integrated with a seismic operation in which all seismic shotholes are logged. A normal day's operation involves logging from 6 to 10 shotholes. This number of holes is normally required for a day's shooting in this area and represents no loss of time for the seismic crew.

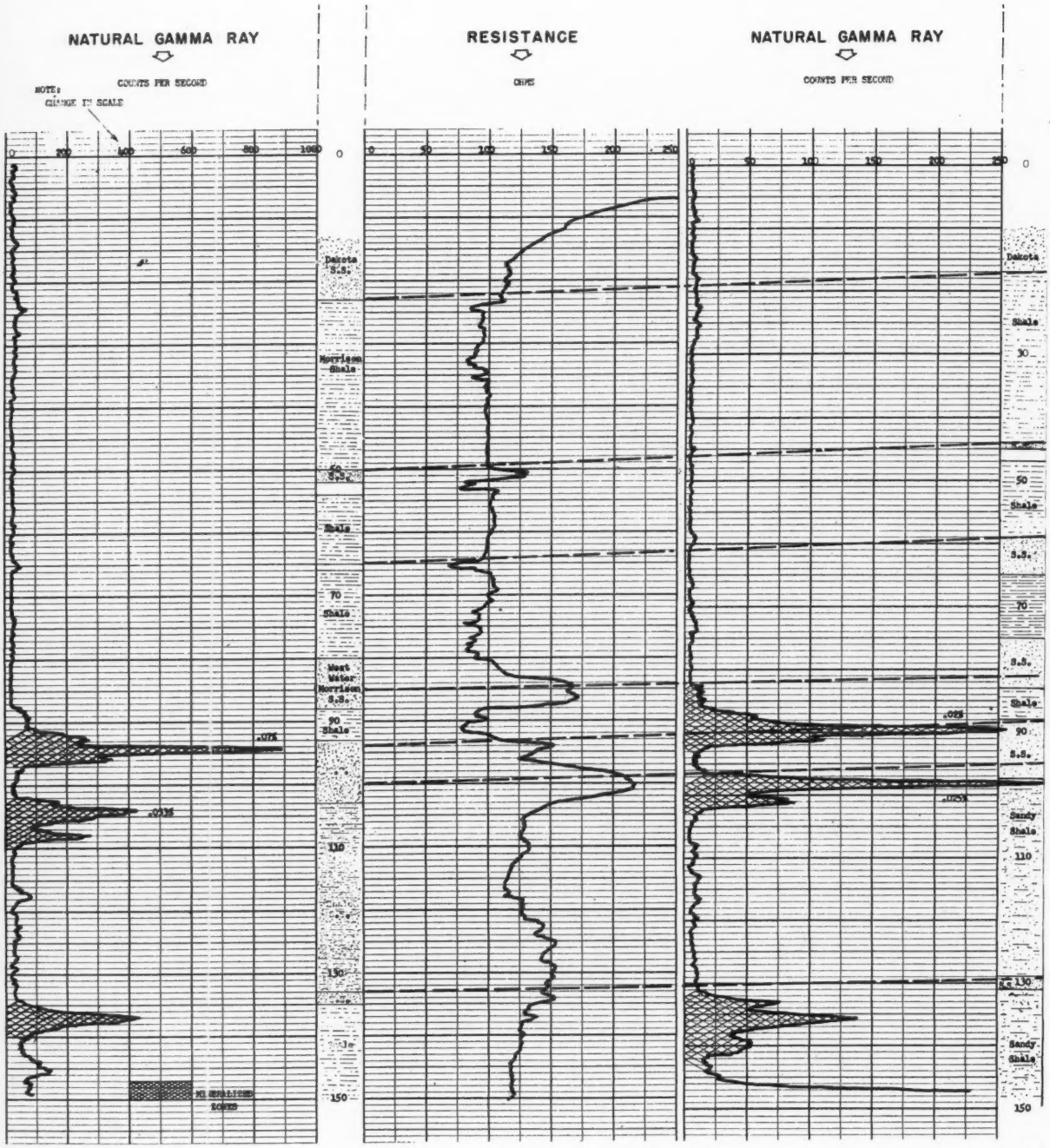
RADIOMETRIC ASSAYING

When a radioactive anomaly is encountered, it is necessary to know what percent uranium oxide has been detected, and whether or not the source of the anomaly can be considered to be an ore body. Unfortunately, a measurement of radiation intensity does not necessarily yield information directly related to ore concentration, since such effects as radium-thorium ratio, inequilibrium, and ore type will materially change any calibration factor. However, for a known area, the proper use of gamma-ray logs and calibration will allow a radiometric assay value to be obtained which agrees with chemical analysis within approximately 15 to 50 percent.

It is necessary first to relate the response of the instrument as indicated by the cps deflection of the gamma-ray trace to intensity in microroentgens per hour. This requires a calibration curve, as shown in Figure 5.

The indicated intensity of radioactivity must be corrected for bed thickness, logging speed, time constant, and diameter of hole. The following general expression can be written:

$$I = I_0 K k_d, \tag{1}$$


NATURAL GAMMA RAY
COUNTS PER SECOND
NOTE: CHANGE IN SCALE
0
200
400
600
800
1000
RESISTANCE
OHMS
0
50
100
150
200
250
NATURAL GAMMA RAY
COUNTS PER SECOND
0
50
100
150
200
250
Dakota S.S.
Morrison Shale
Shale
70
Shale
Upper Water Morrison S.S.
90
Shale
110
130
150
.025
.0125
MINERALIZED ZONES
Dakota
Shale
30
50
Shale
S.S.
70
S.S.
Shale
.025
90
S.S.
.0125
Sandy Shale
110
130
Sandy Shale
150
X-13
X-14

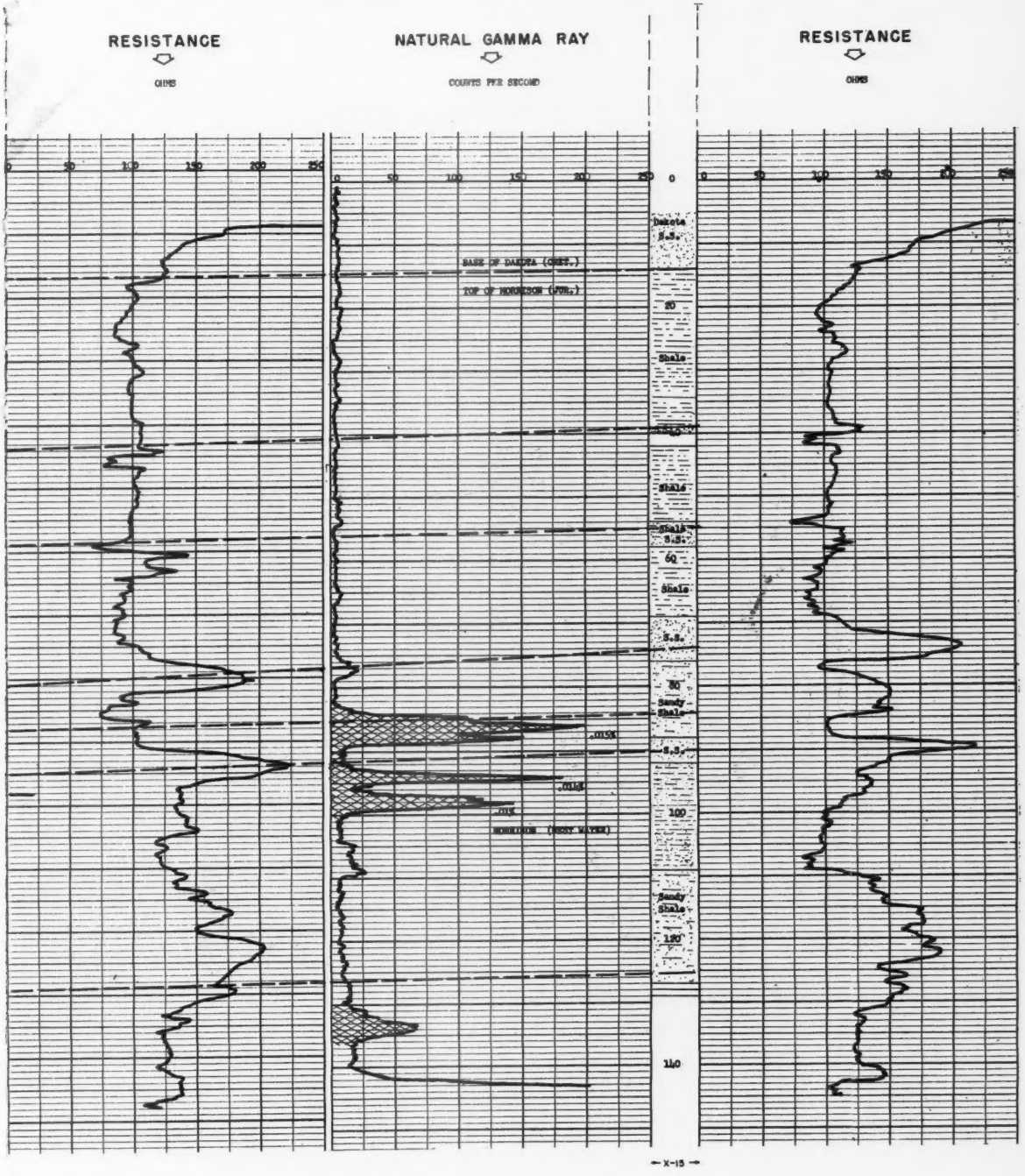


FIG. 6. Gamma-ray-resistance log correlation.

where

I_0 = true intensity in μr/hr
I = indicated intensity in μr/hr
K = correction factor for bed thickness, logging rate, and time constant
k_d = correction factor for hole diameter.

FIG. 7. Typical logging truck in operation with boom assembly.

The factor K is obtained from a curve relating K to bed thickness for various logging rates at a fixed time constant. Such a curve is shown in Figure 10. This curve was obtained experimentally by logging through an artificial borehole having alternate layers of ore and sand. The ore layers were of identical activity but of different thickness. A family of these curves is prepared for each time con-

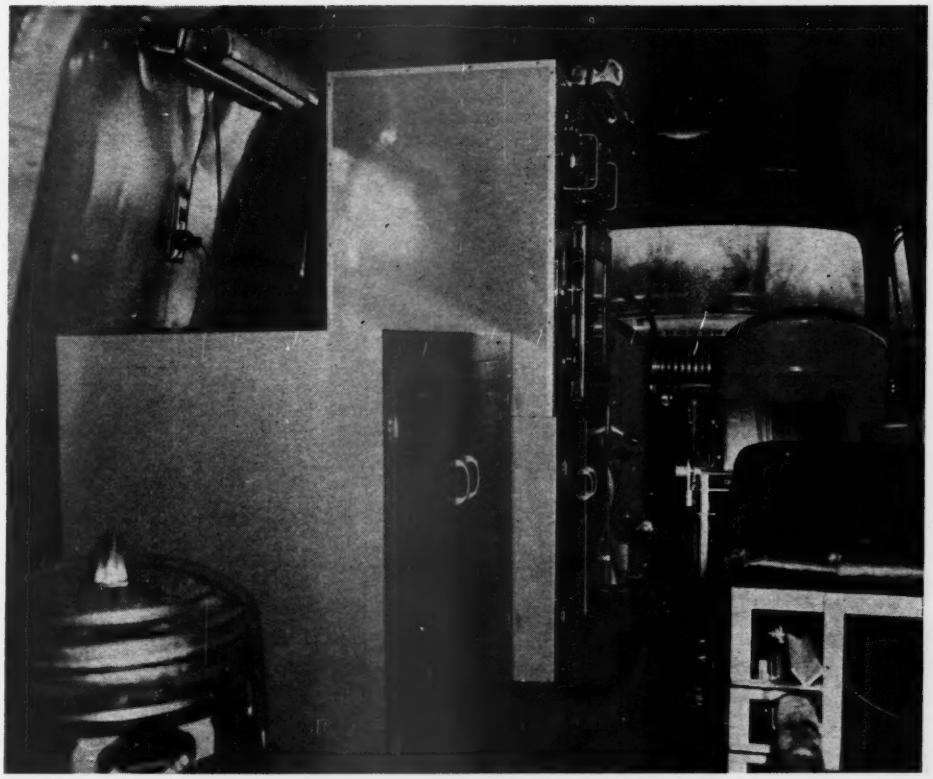


FIG. 8. Internal view of logging truck.

FIG. 9. Field logging operation.

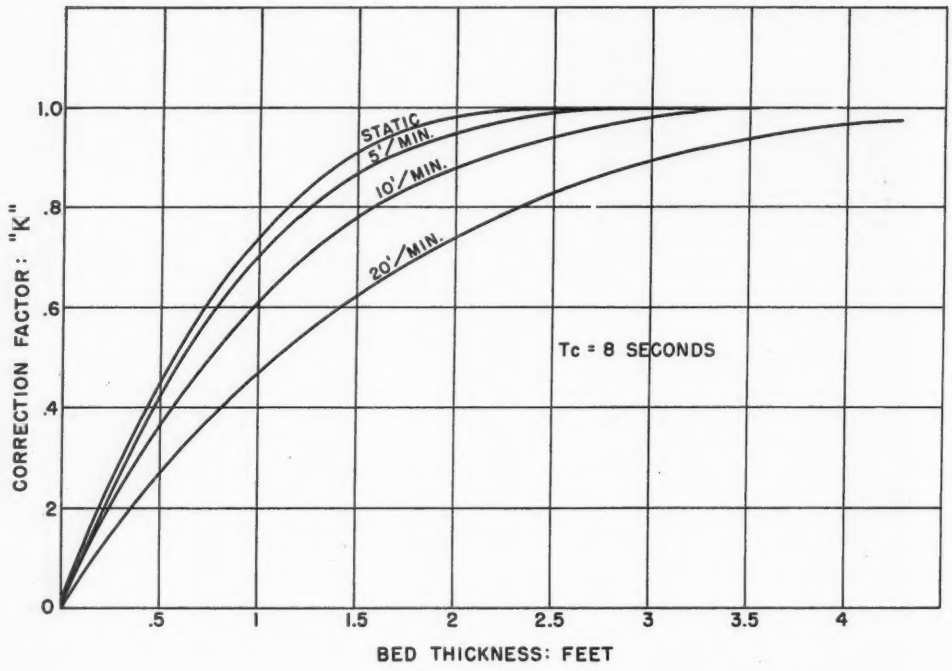


FIG. 10. Rate and bed correction factor.

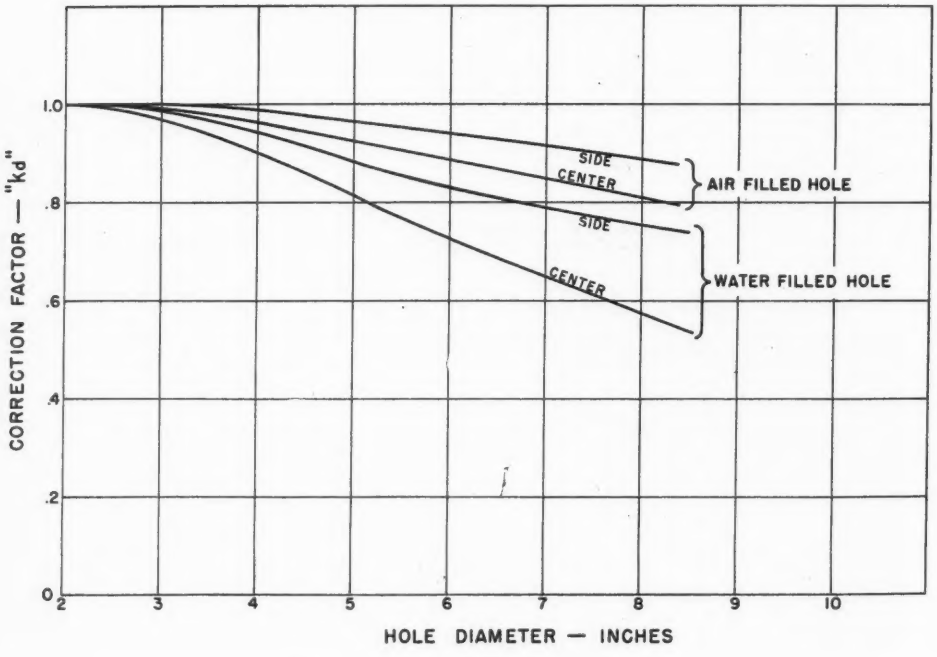


FIG. 11. Borehole diameter correction.

stant. By logging at a very slow speed, or by taking static measurements opposite the bed of interest, the effect of time constant is eliminated.

The factor k_d is obtained from curves as shown in Figure 11. These experimental curves show the effect of changing the diameter of boreholes in relatively thick formations. There is a considerable difference in response depending upon whether the borehold is fluid-filled or air-filled. It also makes a difference whether the probe is in the center of the hole or against the side of the hole. The center-of-the-hole curves are used since they represent the least favorable condition. Thus, by the use of the above curves and equation (1), the indicated intensity reading can be corrected to give the actual intensity value.

By placing the probe in a thick ore body of known concentration, a conversion factor can be obtained relating U_3O_8 to intensity in μr/hr. This may be expressed by the relation

$$\text{Percent } U_3O_8 = CI_0, \tag{2}$$

where C is the conversion factor.

This conversion is useable only for a known mineral in equilibrium. It is recommended that the factor C be obtained from a reliable chemical assay of representative ore samples taken in the area and from the formation of interest. A typical value of C used in the Colorado Plateau is 1.9×10^{-4} for the Model 2201 probe. The procedure for making an assay is as follows:

1. From the log, select the zone of interest and measure the bed thickness. NOTE: The bed thickness is obtained from the separation between the inflection points on the skirts of the anomaly. Beds less than 6 inches cannot be estimated since they are less than the length of the sensing unit for the Model 2201 probe.
2. Obtain a representative cps value of the anomaly from the log.
3. Convert the measured cps value to μr/hr from the calibration curve, Figure 5.
4. Knowing the logging speed and time constant setting, obtain a value for K from curves similar to those of Figure 10.
5. Knowing the hole diameter (bit size), obtain a value for k_d from Figure 11, using the appropriate curve for an air-filled or fluid-filled hole with the probe in the center of the hole.
6. Determine I_0 from the indicated value of intensity by applying the values of K and k_d to equation (1).
7. Apply the conversion factor for the particular area to I_0 to obtain the equivalent U_3O_8 assay value using equation (2).

GEOPHYSICAL EXAMPLE

A uranium exploration survey was undertaken for the Rocky Mountain Uranium Corporation of Dallas, Texas to evaluate its Green Dragon Prospect in Emery County, Utah. The original claims had been staked because of a radio-

FIG. 12. Contour map of elevation and maximum isorad values of the Chinle horizon, Green Dragon Prospect.

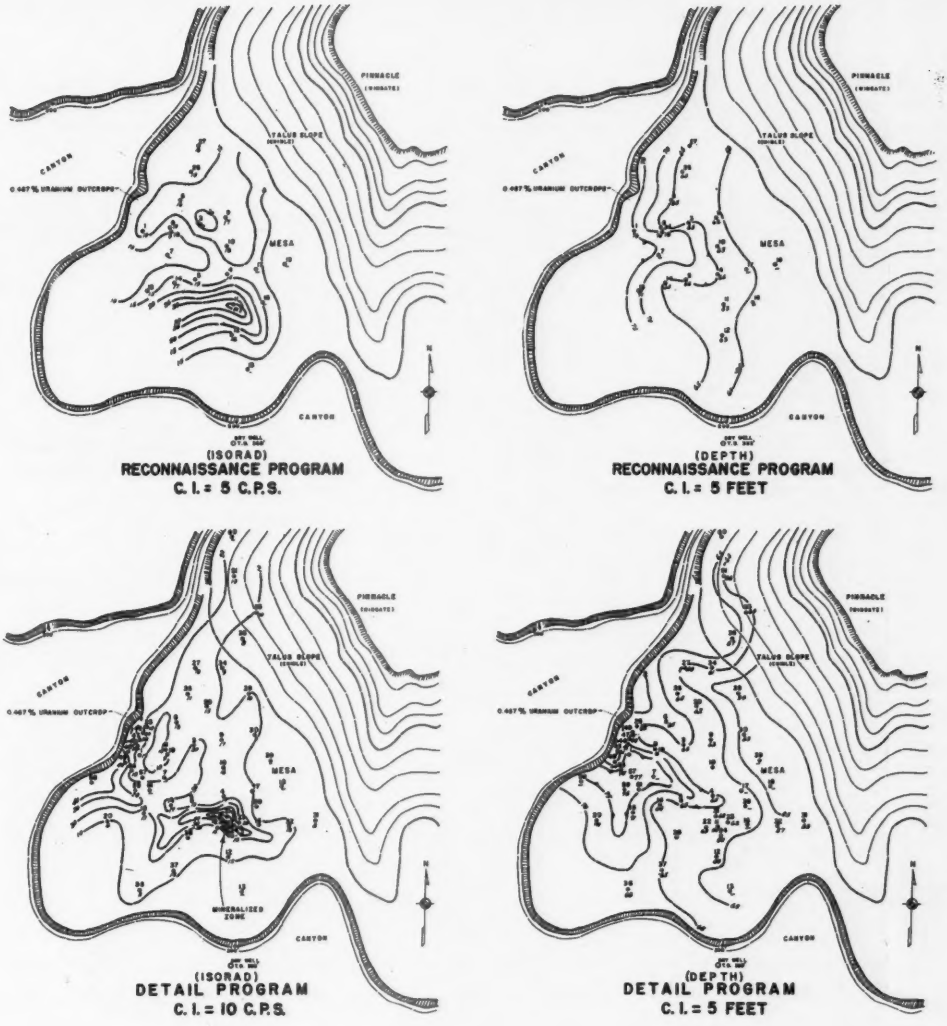
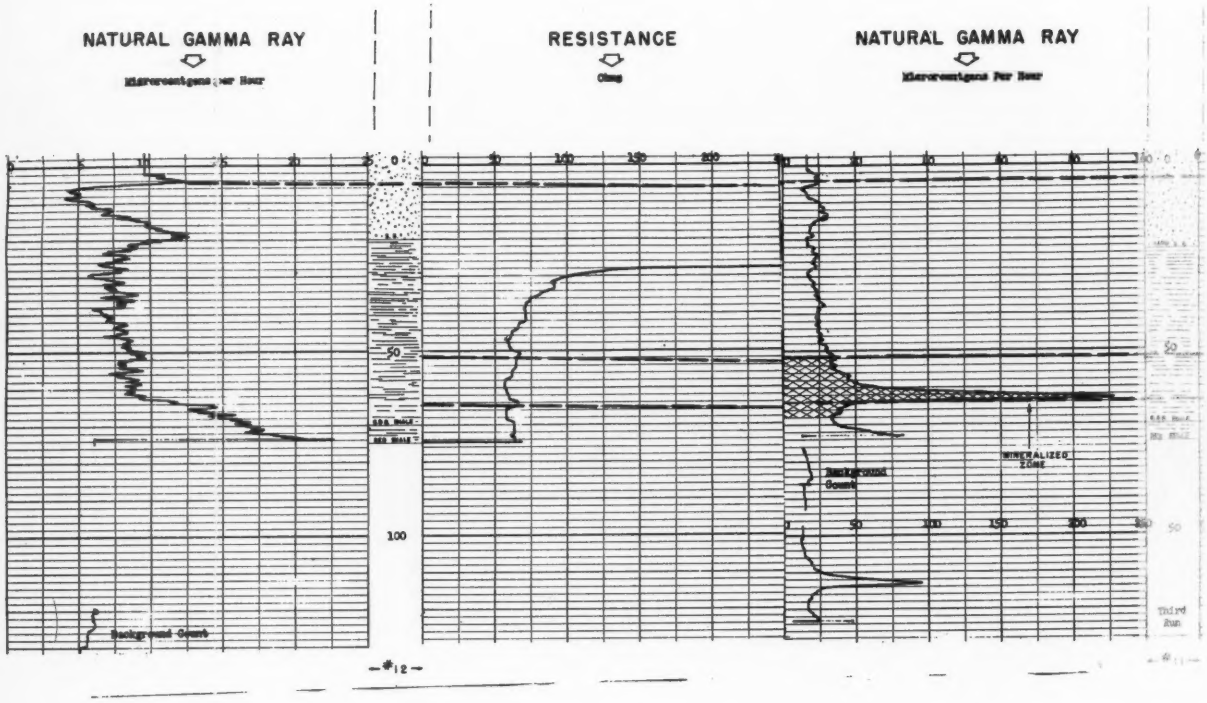
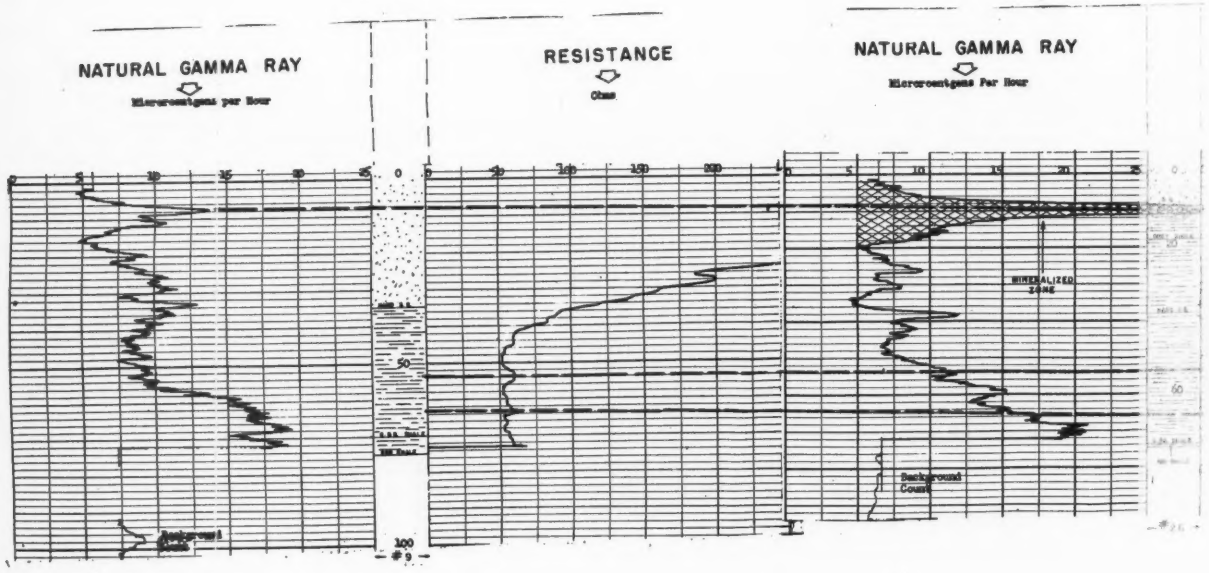


FIG. 13. Contour map of elevation and maximum isorad values of the Shinarump horizon, Green Dragon Prospect.


NATURAL GAMMA RAY
Microroentgens per Hour
RESISTANCE
Ohms
NATURAL GAMMA RAY
Microroentgens Per Hour
MINERALIZED ZONE
Background Count
#12


NATURAL GAMMA RAY
Microroentgens per Hour
RESISTANCE
Ohms
NATURAL GAMMA RAY
Microroentgens Per Hour
MINERALIZED ZONE
Background Count
#9

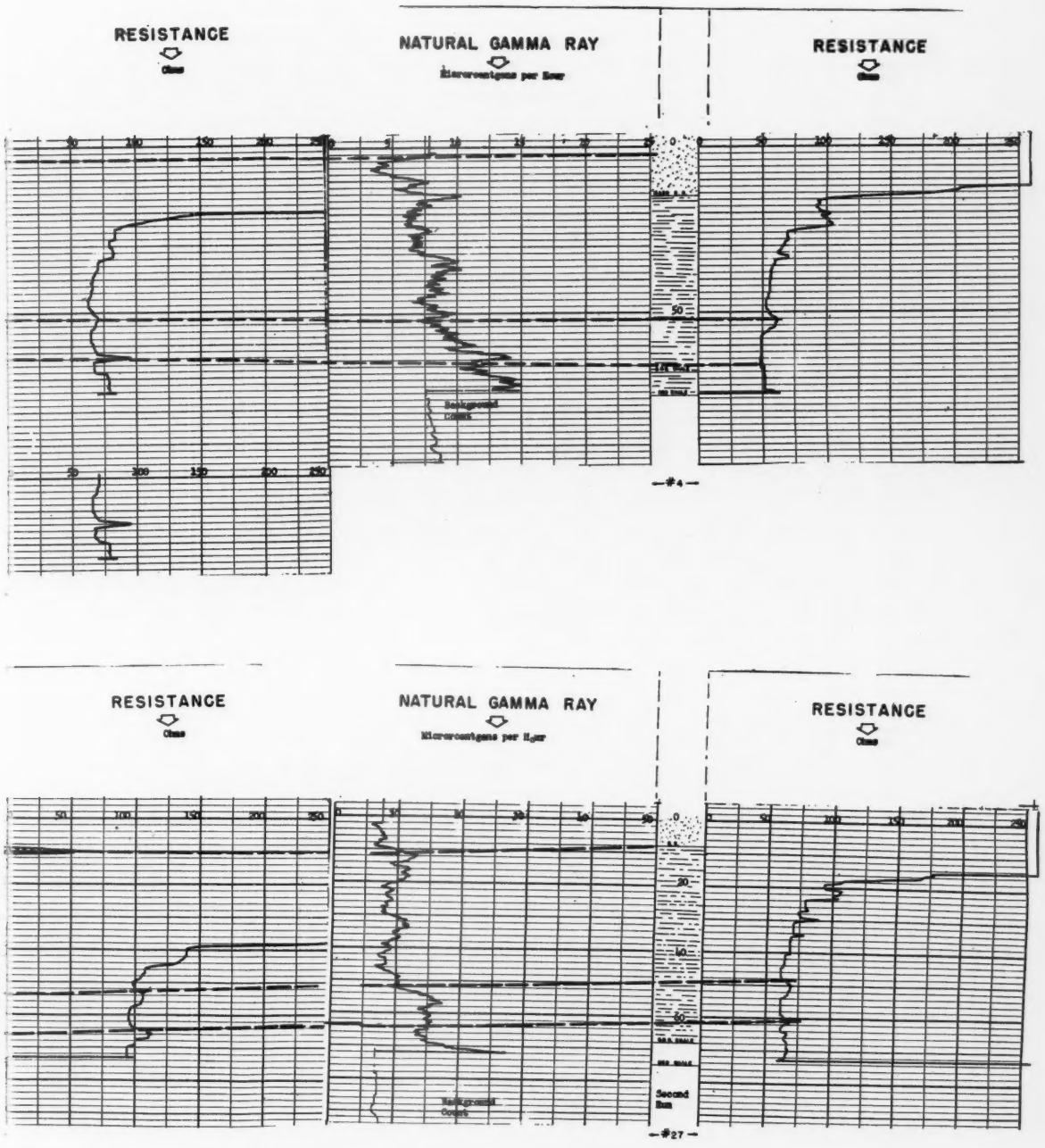


FIG. 14. Typical gamma-ray-resistance correlation cross-sections of the Green Dragon Prospect.

active anomaly encountered in an exposure of the Shinarump formation in a nearby cliff. The properties are located in a mesa that is approximately 700 feet above the canyon floor. The mesa is the result of the extreme surface erosion that typifies this and the adjacent Grand Canyon area.

Access roads were built up to the mesa and a reconnaissance drilling program was inaugurated utilizing standard heavy-duty shothole drills. These holes were then logged by Century's Gamma-R Logger and structural and isorad maps were prepared. It was possible to correlate three major gamma-ray anomalies and five anomalies on the resistance logs. Structural contour maps were prepared from the correlatable events on the resistance logs. Isorad maps were made by mapping the intensity of radioactivity shown on the gamma-ray logs at the same depth as the corresponding geological tops which had been correlated from the resistance logs. Thus, it was possible to depict the radioactivity or mineralization at definite geological markers.

Two sets of maps are shown in Figures 12 and 13. These maps are schematic only and present a comparison between two of the reconnaissance and detailed mineralization zones which were mapped, thus indicating the results of the reconnaissance and detailed exploration programs. It is interesting to study the development of the rather pronounced channeling shown by the structural maps and the mineralized zones that are very often found associated with such erosional subsurface features in this area.

The Chinle horizon maps are shown in Figure 12. The isorad map of the reconnaissance program indicates an increase in radioactivity to the west. This interpretation was strengthened by the known outcrop of ore found in the cliff at the western edge of the mesa. The subsurface map prepared from the resistance logs of the reconnaissance program suggests a possible channeling effect at this depth. These two factors were used to recommend a detailed program to investigate further the subsurface mineralization of the mesa.

The detailed isorad map substantiates the reconnaissance interpretation and clearly outlines the carnotite ore body at the Chinle depth. The subsurface channel is further developed at Chinle depth, as is shown by the detailed resistance-depth map.

The Shinarump horizon maps are shown in Figure 13. The isorad maps indicate the development of a separate carnotite ore deposit at Shinarump depth. The detailed map establishes that this is a local ore deposit only; however, it is, in general, within the confines of the subsurface channel as outlined by the detailed depth map prepared from the resistance logs. The channel is more clearly developed at this depth.

The two cross-sections of Figure 14, show some of the gamma-ray logs obtained from test holes which are approximately 60 ft apart. Shallow and deep mineralization zones are shown. The resistance logs obtained on this project are below standard, as the holes would not hold the drilling mud and were water-filled prior to logging. The off-scale reading on the upper portions of the resistance

logs indicates the level at which the probe came out of the water in the holes. Sandstone stringers in the Chinle and Shinarump formations were found to be continuous over the area and were used as correlation points on the resistance logs. Gamma-ray anomalies are shown near the base of the Chinle and of the Shinarump formations. These cross-sections and maps illustrate the type of geological and geophysical information that can be derived from combination gamma-ray-resistance logging. By such a method properties can be evaluated and mineralized zones can be blocked out without resorting to expensive mining or core drilling.

SUMMARY

The oil and mining industries, which are both in the business of finding and and developing natural resources, are particularly qualified to explore for and develop radioactive minerals. This is due to the fact that the thinking, talents, processes, and methods used by the oil and mining industries can be readily transferred to the task of finding and developing minerals necessary for atomic energy.

It is believed that uranium prospecting requires logging for determining quantitative radioactive mineral content as well as for obtaining geological information. The mere random sampling for radioactivity, or the "yes or no" type approach, is considered inadequate. For this reason, the Gamma-R Logger was developed. The following information can be derived from the Gamma-R log:

1. Measure of the quality and quantity of radioactive minerals encountered in the boreholes.
2. Lithology.
3. Stratigraphy and concomitant structural information.

The Gamma-R logging equipment described has proven to be efficient and trouble-free, and has yielded high-quality logs. It has made it possible for the geophysicist, who is trained in the science of subsurface exploration, to apply his skill in the exploration for uranium.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of Mr. C. W. Zimmerman in the instrumental development; of Mr. Archie Nicol for assistance in field operation techniques; and of the Atomic Energy Commission, Climax Uranium Company, and Rocky Mountain Uranium Corporation for their permission to use information obtained in actual field practice.

GEOPHYSICS, VOL. XX, NO. 4 (OCTOBER, 1955), PP. 860–870, 4 FIGS.

A LOW FREQUENCY ELECTRICAL EARTH MODEL*

WILLIAM C. PRITCHETT†

ABSTRACT

A general earth model is described which simulates the earth when excited by currents either conductively coupled to the earth by electrodes or inductively coupled to the earth by loops. Consideration of model equations showed that a material with a resistivity of approximately 10^{-4} ohm-meters was desired for use in the model. Although suitable materials with this resistivity were not known, it was found that fine bronze wheel grindings held together by wax did have the required macroscopic resistivity. Using this model, surface measurements were made employing a modified Wenner spread "one mile" in length. Only minor anomalies resulted from a simulated salt dome "three-quarters of a mile" in diameter and "one-half mile" below the surface.

INTRODUCTION

An investigation was undertaken to determine the potentialities of various low frequency electrical prospecting techniques under controlled laboratory conditions. Specifically to be investigated was the possibility of surface detection of large, highly resistive structures such as salt domes at depths of several thousand feet. Since a salt dome has a high resistivity and is large in both vertical and horizontal extent, it should be the easiest type of buried structure to detect. A preliminary analysis led to the conclusion that earth structures at depths of several thousand feet could best be detected using low frequency currents (less than 20 cps) conductively coupled to the ground through electrodes separated by a mile or more.

Laboratory investigation of the potentialities of various field measurement techniques required an earth model, of practical size, representing many cubic miles of earth. The purpose of this paper is to discuss a technique which is advantageous in modeling the earth electrically.

MODELING EQUATIONS

The basic modeling consideration is that the ratio of wavelength in the earth to wavelength in the model must equal the scale factor (the ratio of earth dimensions to model dimensions). For low frequency, substitution in the formula for wavelength[1] yields:

$$[Fd]^2 = \left[\frac{\rho_e}{\rho_m}\right]\left[\frac{f_m}{f_e}\right]. \qquad (1)$$

* Presented at the Midwestern Regional Meeting of the Society in Dallas, Texas, November 18. 1954.

† Atlantic Refining Company, Dallas, Texas.

[1] $\lambda = 2\sqrt{(\pi\rho/f\mu)}$ is the wavelength, f is the frequency, μ is the magnetic permeability in MKS units.

Where:

$$F_d = \text{scale factor} = \frac{\lambda_e}{\lambda_m} = \frac{\text{earth wavelength}}{\text{model wavelength}}$$

ρ_e = earth resistivity

f_e = earth frequency

ρ_m = model resistivity

f_m = model frequency

The observed signal is directly proportional to the potential spread, to the resistivity of the medium, and to the current density in the medium. The transfer impedance in the model is then related to the transfer impedance in the earth by the following equation:

$$\left(\frac{V}{I}\right)_m = \left(\frac{V}{I}\right)_e \left(\frac{\rho_m}{\rho_e}\right)(F_d) = \left(\frac{V}{I}\right)_e \sqrt{\left(\frac{\rho_m}{\rho_e}\right)\left(\frac{f_m}{f_e}\right)}, \qquad (2)$$

where

$\left(\frac{V}{I}\right)_m$ = transfer impedance in volts per ampere in the model

$\left(\frac{V}{I}\right)_e$ = transfer impedance in volts per ampere in the earth.

Equation 1 indicates that a given modeling scale factor can be obtained by adjusting the resistivity ratio, the frequency ratio, or both. Consider first the consequences of holding the frequency constant and varying only the resistivity ratio. If the assumed scale factor is three inches = one mile, the model resistivities must be reduced, relative to the corresponding earth resistivities, by a factor of 4.45×10^8. It follows that this solution yields model signals in volts per ampere which are smaller by a factor of 2.1×10^4 than the small earth signals to be simulated. A model of this type, consisting of stacked metal plates rigidly clamped together, was used by Yost et al. (1952) to investigate the use of horizontal loops both as current input and signal output devices. They overcame the low model signal level by use of multiple turn input and output loops. For a conductively excited model, in order to obtain a measurable signal an impracticably large current would have to be applied. Even if large currents were used, a model composed of metal plates stacked and clamped together in this manner would not be usable except with special excitation. Such a model is probably satisfactory when excited by a horizontal loop since none of the induced currents have any vertical components, but if the current is conductively coupled to the model, large vertical current components exist. Unless the sum of the contact resistances between the stacked metal plates were low compared to the sum of the vertical

resistances of the plates, the resulting anisotropy would impede the vertical flow of current and invalidate the model. Such excellent contact between metal plates was found to be impracticable to attain. Solid metal models could be used but they would not be easy to work with.

Now consider the case where the model resistivities are the same as the earth resistivities. This requires the model frequencies to be larger than the earth frequencies by a factor of 4.45×10^8. The required model frequencies would then range from those used in television to those used in radar. The use of such frequencies would undoubtedly lead to formidable instrumentation difficulties and will not be considered further. However, it should be pointed out that in this case the model signal is stronger than that in the earth by a factor of 2.1×10^4.

A compromise between the two alternatives considered above yields a usable signal level with reasonable frequencies. Consider the situation in which the model resistivities are reduced by the scale factor 2.1×10^4 relative to the earth resistivities, and the model frequencies are increased by the same scale factor relative to the earth frequencies. In this case the signal levels in the model and in the earth are equal. The required model frequencies are reasonable, ranging from those above audio to those below broadcast frequencies. It is of interest to point out that only in this third case is the wavelength in the air properly scaled (by the factor F_d). This guarantees that any air coupling between the lines has the same effect in the model as in the earth. Since air coupling is thought to be negligible, no attempt was made to adhere strictly to this condition in interpreting the model results. In fact the model data shown here would represent a 17 ohm-meter earth if the wavelength in the air were exactly scaled. The data are actually presented as representing a 10 ohm-meter earth at somewhat lower frequencies, as indicated by equation (2)

MODEL MATERIALS

To build a model in which the resistivity is reduced by the scale factor, suitable homogeneous materials with resistivities in the range of 1×10^{-4} to 10×10^{-4} must be obtained to simulate the shales and other low-resistivity earth beds. It would also be desirable to obtain materials with resistivities of the order of 100×10^{-4} ohm-meters in order to be able to model stringers and structures with high, but finite, resistivities. No suitable materials are known which have resistivities in the range of primary interest. The resistivities of several materials which might be considered are given in Table 1. In nature, certain metallic ores, such as galena, do have resistivities in this range but they are not at all homogeneous and they decompose below their melting point, which would make casting difficult.

Consideration was given to devising mixtures of materials of high and low resistivity having macroscopic resistivities in the desired range. A series of empirical tests were made utilizing small metal particles either immersed in liquids, such as brine or mercury, or bonded with such materials as sulfur, lucite, cement,

TABLE I

RESISTIVITIES OF COMMON MATERIALS

Note: The resistivity range of primary interest in earth modeling is 1×10^{-4} to 10×10^{-4} ohm-meters.

Material	Approximate resistivity (Ohm-meters)
Saturated Salt Water	350×10^{-4}
Carbon	0.35×10^{-4}
Graphite	0.08×10^{-4}
Mercury	0.008×10^{-4}
Lead	0.001×10^{-4}
Aluminum	0.0003×10^{-4}
Copper	0.0002×10^{-4}

glue, agar, or wax. Catalytic hardening plastics, including Phenoline[2] and Epon,[3] were also tried as bonding materials.

The necessary characteristics for the bonding material were found to be:

1. It should not require evaporation to harden.
2. It should not react with the metal.
3. It must shrink slightly upon solidication and/or cooling in order to force the metal particles into intimate contact with each other.
4. It must not shrink sufficiently to cause cracking when cast in blocks large enough to use as a model.
5. It must be hard enough when cast to hold the particles in contact for a reasonable period of time.

Phenoline plastic initially seemed to offer the best hope of success when cast in small sample blocks, but was found to set up rather slowly in large samples. The high cost of the plastic and the inability to salvage the metal for re-use were additional disadvantages of Phenoline.

Household paraffin was satisfactory except that the wax was too soft to hold the metal particles in intimate contact. The sample resistivity increased daily until the material become essentially non-conductive. An inexpensive red sealing wax[4] was an excellent binder in small sample blocks but larger blocks cracked upon solidification.

Best results were obtained using a mixture of the red sealing wax and a high-melting wax,[5] and this was the bonding material finally used in the model work.

The model used was prepared as follows: First, ten pounds of the high-melting wax was melted in a small cement mixer which was heated by torches playing on

[2] Phenoline is a product of The Carboline Co., 7603 Forsythe Blvd., St. Louis 5, Missouri.

[3] Epon is a product of The Shell Chemical Co., Box 2633, Houston, Texas.

[4] Princeton Sealing Wax Co., #R-CP Red.

[5] The Atlantic Refining Company, #1115.

the rotating barrel. Ten pounds of the sealing wax was then added and with the temperature held near 260°F the two waxes combined to form a water-thin liquid. Eighty-five pounds of bronze wheel grindings, previously passed through a forty mesh screen, was added slowly to prevent local solidification of wax. After thorough mixing the aggregate was poured into a wooden mold twenty inches in length, ten inches in width, and five inches in height. The aggregate appeared almost dry before pouring but when worked into the mold about $\frac{1}{4}$ of an inch of surplus wax came to the surface and was removed.

The mold was enclosed in an insulated box to allow the model to cool slowly so as to avoid cracking. After cooling, the model was kept at room temperature in a thermostatically-controlled enclosure to minimize thermal stress cycles. The resulting model had a uniform internal resistivity of approximately 0.8×10^{-4} ohm-meters, but the resistivity near the surface was higher and more variable. However, this was not believed to be an important effect. In a two and one-half month period, one end of the model increased in resistivity by only 5%, while the other end increased about 15%. After the model measurements had been completed the model was stored in an unheated building. A year later the resistivity of the first end of the model had increased by 100%; the other end had become essentially non-conductive. These changes were believed to be due to cold flow of the wax. It was concluded that the probable resistivity changes in a model should not be sufficient to affect the results adversely if all measurements are carried out in the first few weeks after the model is formed.

Sample blocks were made using brass or bronze particles of various graded sizes. Various macroscopic resistivities, in the range of interest previously indicated, were thereby obtained.

MEASUREMENT TECHNIQUES AND EQUIPMENT

Figure 1 is a sketch of the model showing the method of applying currents and measuring potentials. A pair of spring-loaded, screen-door hinges anchored to the wooden mold held a $\frac{1}{4}$ inch sheet of lucite flush against the model surface. Threaded holes $\frac{3}{4}$ of an inch apart and arranged in two lines 1/10 of an inch apart were used to hold the electrodes.

In order to make good contact to the model, spring-loaded electrodes made from watch-band holders were threaded and screwed into the desired locations in the lucite plate. Connection to the electrodes was achieved by use of spring-wire clips soldered to enameled wires which were run under the lucite sheet. A capacitive shield over the twisted potential leads from the model to the measuring circuit is not shown in the figure.

Sine wave current, applied to the model from a power amplifier, varied in magnitude from an ampere at the lower frequencies to 25 milliamperes at 150,000 cps. Potential amplitudes and phases were obtained using Lissajou's patterns on a calibrated oscilloscope. Ahead of the oscilloscope was a special low-noise, wide-band, balanced amplifier.

For the current source in the transient studies, a square wave generator was used to turn off and on six no. 807 transmitting tubes used in parallel in a cathode follower circuit. A current decay time (90% to 10%) of less then 0.45 microseconds was achieved with a total current change of 0.64 amperes. Unfortunately, superimposed upon this current transient was a small percentage of approximately 20-megacycle current which did give considerable difficulty in some of the measurements. The transient potential decay curve was displayed on the oscilloscope and photographed.

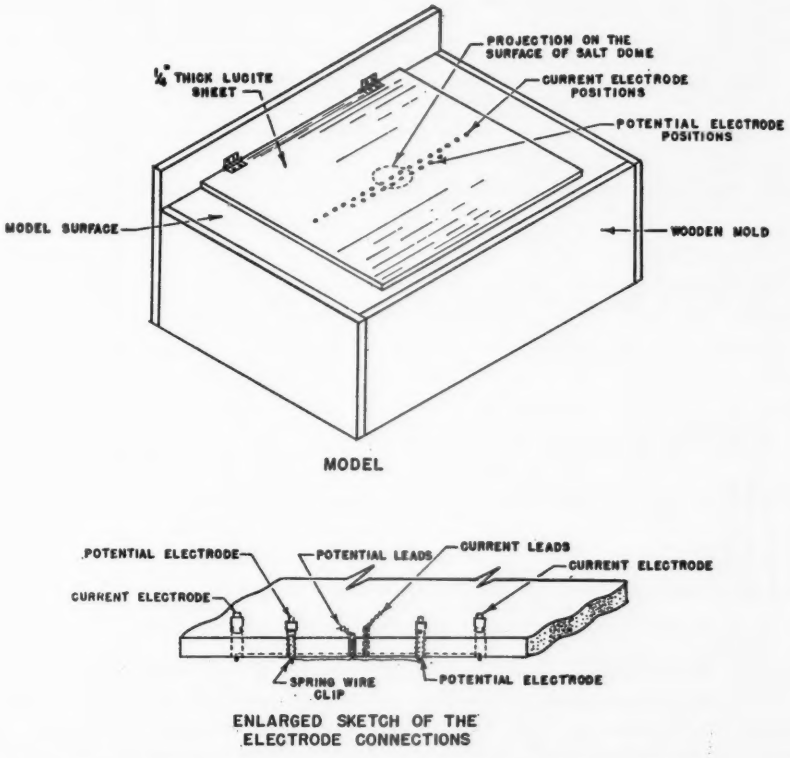


FIG. 1. A Sketch of the model and of the electrodes. The model, composed of bronze particles bonded with wax, was kept in the wooden mold. Electrical connections were made to the model by wires connected to spring-loaded contacts.

RESULTS USING SINE WAVE CURRENTS

Figure 2 shows some model results which represent the response of a ten ohm-meter earth to sinusoidal currents ranging in frequency from 0.3 cps to 50 cps. The potential amplitude measured by a $\frac{1}{4}$ mile spread in response to an essentially collinear, 1-mile current spread is plotted before and after a simulated salt dome was cut into the model beneath the spread. The salt dome represented was

a cylinder $\frac{3}{4}$ of a mile in diameter rising from about 8800 ft. to within $\frac{3}{4}$ of a mile of the surface. Later the depth of burial was reduced to one-half of a mile. It would seem likely that the effect of the dome on the potential at a depth of a half-mile should be larger than, but in the same direction as, the effect of the dome at a depth of $\frac{3}{4}$ mile. It will be noted from Figure 2 that at most frequencies the rather small deviations from the potential measured with no dome present are not consistent with this expectation. It is thought, therefore, that the deviations

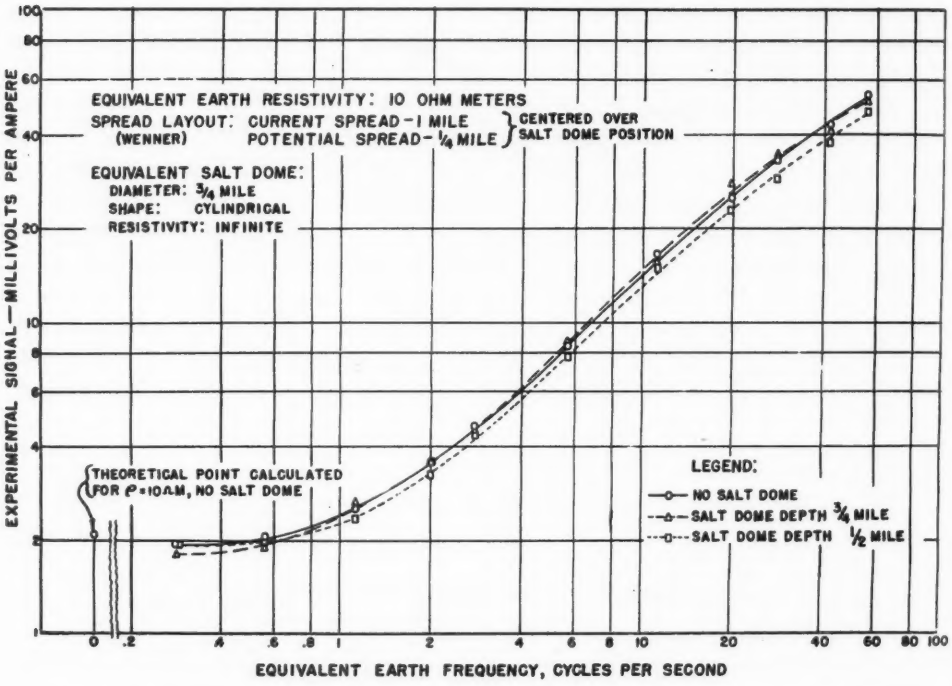

EXPERIMENTAL SIGNAL — MILLIVOLTS PER AMPERE
EQUIVALENT EARTH RESISTIVITY: 10 OHM METERS
SPREAD LAYOUT: CURRENT SPREAD - 1 MILE
(WENNER) POTENTIAL SPREAD - 1/4 MILE
CENTERED OVER SALT DOME POSITION
EQUIVALENT SALT DOME:
DIAMETER: 3/4 MILE
SHAPE: CYLINDRICAL
RESISTIVITY: INFINITE
THEORETICAL POINT CALCULATED FOR ρ = 10 Ω M, NO SALT DOME
LEGEND:
NO SALT DOME
SALT DOME DEPTH 3/4 MILE
SALT DOME DEPTH 1/2 MILE
EQUIVALENT EARTH FREQUENCY, CYCLES PER SECOND

FIG. 2. Experimental variation of the potential amplitude with frequency for steady state currents. Sine wave measurements of potential amplitudes were made at several frequencies before and after the simulated salt dome was cut into the model. The higher the frequency the less the current penetrates into the earth; therefore, the surface potential increases with frequency for a given total current. The effect of the dome is too small to be definitely determined.

shown are not primarily attributable to the domes, but are the result of experimental errors. Data on repeat runs showed similar deviations from run to run.

Figure 3 is a plot of the phase angle of the potential relative to the current for the same measurement conditions as those for Figure 2. The deviations of the curves are consistent with expectation and it appears that the dome $\frac{1}{2}$ of a mile deep caused a phase-angle decrease of five degrees for equivalent frequencies ranging from 0.5 cps to 1 cps. The three-to-four degree phase increase above 11 cps is subject to suspicion, since capacitative coupling and difficulty of ground isolation at the higher frequencies made reproducibility quite poor.

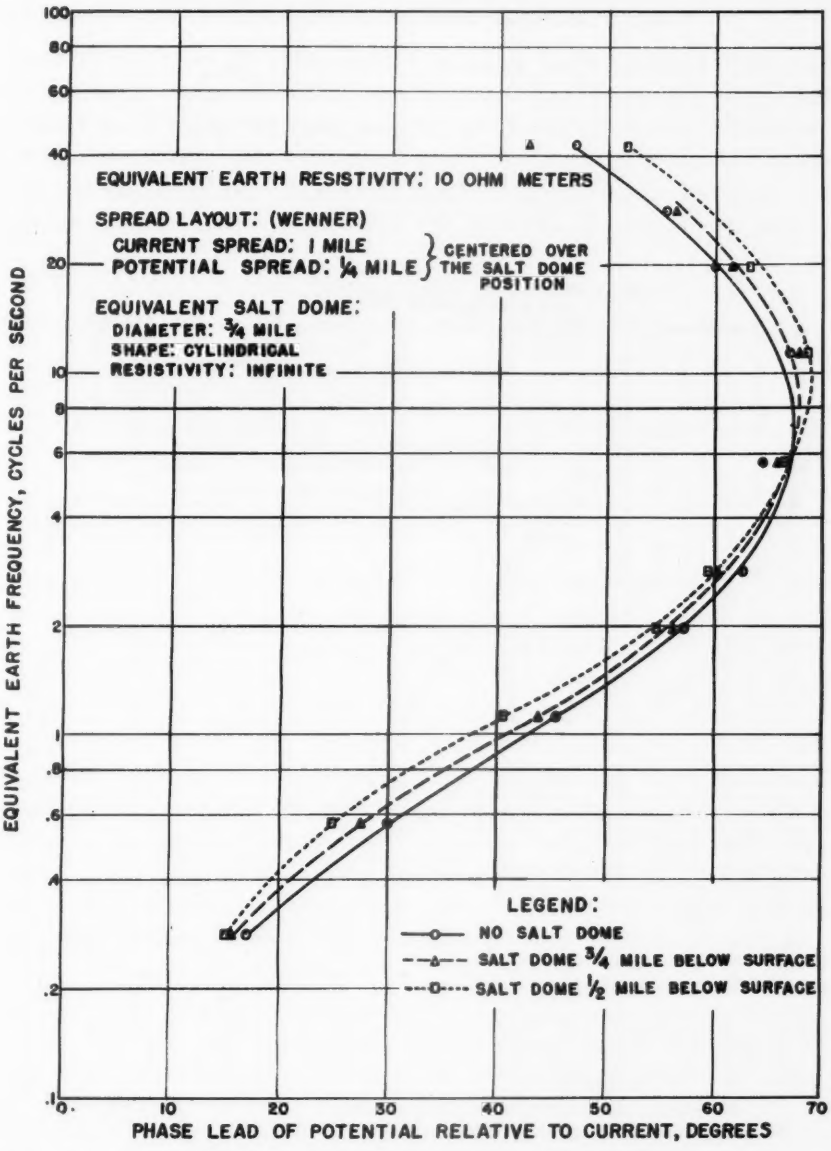


FIG. 3. Experimental phase variation with frequency for steady state currents. Phase measurements before and after the simulated salt dome was cut into the model are significantly different at the lower frequencies. The phase measurements above 5 cps were not very reproducible and may well be in error.

Current spreads of two miles and four miles were also tried, with results that were similar to those shown. The best anomalies resulting from the salt dome at a depth of $\frac{1}{2}$ mile probably did not exceed ten percent in amplitude nor five degrees in phase.

RESULTS USING TRANSIENT CURRENTS

The transient response of the model was measured in response to current step functions. Figure 4 gives the response of the model for the same current and potential arrangements used in obtaining the data given in Figure 2 and Figure 3. The response of both a ten ohm-meter and a two ohm-meter earth can be determined by using the proper time and signal level scales. An equation developed by Yost (1952) was used in deriving the following equation, which was then

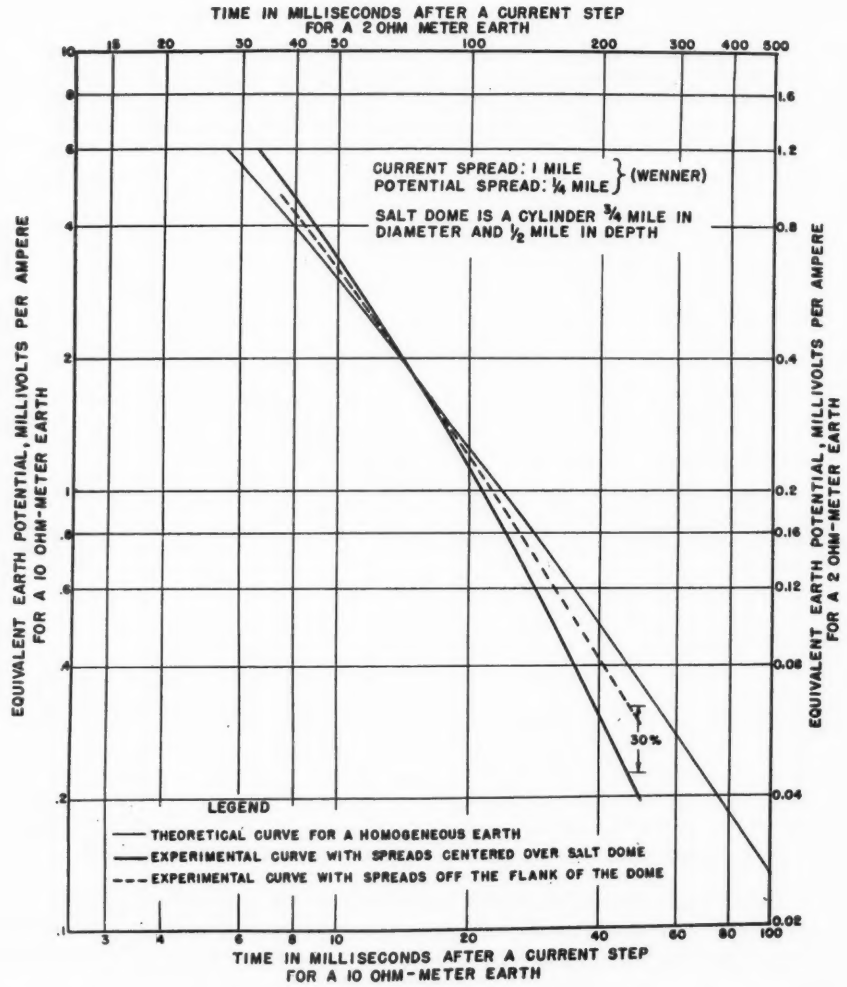

TIME IN MILLISECONDS AFTER A CURRENT STEP FOR A 2 OHM METER EARTH
CURRENT SPREAD: 1 MILE
POTENTIAL SPREAD: ¼ MILE
(WENNER)
SALT DOME IS A CYLINDER ¾ MILE IN DIAMETER AND ½ MILE IN DEPTH
30%
EQUIVALENT EARTH POTENTIAL, MILLIVOLTS PER AMPERE FOR A 10 OHM-METER EARTH
EQUIVALENT EARTH POTENTIAL, MILLIVOLTS PER AMPERE FOR A 2 OHM-METER EARTH
LEGEND
THEORETICAL CURVE FOR A HOMOGENEOUS EARTH
EXPERIMENTAL CURVE WITH SPREADS CENTERED OVER SALT DOME
EXPERIMENTAL CURVE WITH SPREADS OFF THE FLANK OF THE DOME
TIME IN MILLISECONDS AFTER A CURRENT STEP FOR A 10 OHM-METER EARTH

FIG. 4. Experimental transient response. The simulated salt dome caused a decrease in the transient surface potential at the longer times after a current step. At relatively short times after a current step the apparent effect of the dome is to increase the measured potential. The correlation between the theoretical and experimental curves is considered to be reasonable.

used to compute the theoretical curve of Figure 4:

$$V = V_0 - \frac{I_m}{4\pi\sigma}\sum_{i=1}^{2}\sum_{j=1}^{2}(-1)^{i+j} \cdot \left\{\left(2\gamma^2 x_{ij} + \frac{1}{x_{ij}}\right)[\operatorname{erf}(\gamma x_{ij})] + \left(\frac{2\gamma}{\sqrt{\pi}}\right)[e^{-\gamma^2(x_{ij})^2}]\right\} \tag{3}$$

where

$$\gamma = \sqrt{\frac{\mu\sigma}{4t}}$$

x_{ij} are the four distances from the ends of the current spread to the ends of the potential spread,
I_m is the current step in amperes,
V_0 is the response to a dc current equal in magnitude to the current step, and
t is the time in seconds after the current step.

With the salt dome at a depth of ½ mile, data were obtained both with the spreads centered over the simulated dome and with the spreads off the flank of the dome (where the effect of the dome should be minor). The correlation of the latter curve with the theoretical curve is fair. The differences that are present could be accounted for by errors in the timing and by other experimental errors. The most diagnostic effect of the presence of the dome is a decrease in the signal level at the longer times after the current step (30% decrease at 47 milliseconds for a 10 ohm-meter earth). At the earlier times (less than 10 milliseconds) the apparent effect of the dome's presence was to increase the signal by a small percentage. The integral of the potential over the time interval of 8 to 47 milliseconds (assuming a 10 ohm-meter earth) is almost independent of the position of the spreads with respect to the dome. Integration over an earlier time interval should yield a "signal high" over the dome whereas integration over a later interval should yield a "signal low" over the dome.

Similar results were obtained with an equivalent current spread of two miles. Measurements made by Yost et al. (1952, p. 815) on metallic models excited by horizontal loops yielded similar anomalies resulting from simulated salt domes.

Field measurements of the effect of salt domes on the transient response of the earth have been reported by Lewis[6] (1948).

CONCLUSIONS

A material with a resistivity in the range of 1×10^{-4} to 10×10^{-4} ohm-meters would have many advantages in electrically modeling the earth. Such a material is

[6] Lewis measured a definite anomaly over the Long Point dome, which is buried 1,000 feet beneath the surface.

not found in nature. However, materials composed of wax-bonded metal particles were made which exhibited resistivities in the desired range. Using one such material a model study employing a modified Wenner spread was carried out to determine the effect of a simulated salt dome. The salt dome studied yielded rather small anomalies. The accuracy and scope of the model studies were limited by the following factors:

1. Changes in the resistivity of the model.
2. Coupling of current and potential circuits to each other and to ground.
3. The relatively slow decay of the applied current in the transient test, which seriously delayed the time at which accurate potential measurements could begin.
4. Noise in the potential amplifiers.
5. Timing errors in measuring the transient data (resulting from the nonlinearity of the horizontal sweep of the oscilloscope).

The effect of model resistivity variations can be minimized by carrying out the measurements rapidly.

The author wishes to acknowledge the help of Joe F. Felber in making the model, W. H. Luehrmann in taking some of the data reported, and H. F. Dunlap in supervising the project.

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Yost, W. Jacque, Caldwell, R. L., Beard, C. I., McClure, C. D., and Skomal, E. N., 1952, The interpretation of electromagnetic reflection data in geophysical exploration, Part II: v. 17, p. 806–826.

GEOPHYSICS, VOL. XX, NO. 4 (OCTOBER, 1955), PP. 871–885, 10 FIGS.

LINE SPACING EFFECT AND DETERMINATION OF OPTIMUM SPACING ILLUSTRATED BY MARMORA, ONTARIO MAGNETIC ANOMALY*

W. B. AGOCS†

ABSTRACT

The airborne magnetometer data of the Marmora iron ore deposit at Marmora, Ontario have been used as an example to show the results obtained by the use of various line spacings ranging from 1 mile to ¼ mile. The maps show how easy it is, in any type of geophysical survey, to miss a feature of economic value if the line spacing is too coarse.

The probability equations are given for the crossing of randomly oriented features whose maximum dimension is less than the spacing of the control lines for circular, elongate, and rectangular outlines. The equations are $P=D/S$; $P=2L/\pi S$; $P=2(L+W)/\pi S$; $P=A/\pi S$; $P=(2L(S+T)-L^2)/\pi ST$; and $P=(D(S+T-\pi D))/ST$; respectively where P is the probability; D is the diameter; L is the length; W is the width; and S and T are line spacings.

INTRODUCTION

The effect of station spacing and the effect of the distance between the plane of observation and the plane of the source of potential field anomalies have been frequently studied by geophysicists.

The purpose of this paper, however, is to illustrate the effect of *line spacing* on the resultant mapped magnetic anomaly for a known magnetite mass, and to present the elementary probability equations as worked out by Czuber (1908) for the optimum control spacing for detecting a particular type of feature. The effect of line spacing, which is illustrated by the magnetic maps presented herewith, would be comparable in any type of geophysical survey, since the contours between lines are of necessity interpolated.

From practical and theoretical studies of potential field functions, it is found that the following effects are obtained by increasing the distance between the plane of observation and the plane of the source of the anomaly: (1) the magnitude of the anomaly decreases by some inverse power of this distance depending upon the shape of the body; (2) the resolution of the individual anomalies decreases; and (3) the areal extent of the anomalies increases. The effect, therefore, of increasing the altitude of observation in airborne geophysical surveys is of considerable interest in searching for anomalies whose source is at or near the earth's surface, since the optimum level at which measurements are made is such that a maximum of resolution is obtained with a minimum of local differential effects.

The magnetite iron ores have a density ranging from 3.2 to 4.5 grams/cm.^{3} For practical purposes this represents a range of 8 to 10 cubic feet per ton of ore,

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depending upon the magnetite content. For a million tons of ore, the volume would be 8 million cubic ft, corresponding to a cube 200 ft on a side. For a small operation this may be of interest, but for a large operation a limit of 20 million tons may be assumed, corresponding to a cube 545 ft on a side. Marmora has 20 million tons of ore within a depth range of 500 ft, an areal extent of 320 thousand square ft, a length of 2,400 ft, an average width of 135 ft, and a maximum width of 500 ft. (Anon., 1953) From these considerations, it is possible to arrive at values for the areal extent of iron ore concentrations of different shapes and distributions of ore, and the resultant anomalies in the magnetic or gravimetric fields.

The sedimentary radioactive ores, and the weathered outcrops of other radioactive ores, present a slightly different problem. The radioactive material in these ores contributes very little to the density of the country rock, whose mean density would be of the order of 2.6 grams/cm^3, or 12½ cubic ft per ton of ore. A 10,000-ton radioactive ore body with a thickness of one foot would have an areal extent of 125,000 square ft, which could be distributed as a vein 1 ft wide and 125,000 ft long, or as a square 385 ft on a side. These values permit an estimate of the probable radiometric anomaly.

The areal extent of a petroleum structure containing one million barrels is controlled by the thickness of the producing section, the porosity, and the saturation. Assuming a 20% porosity, a 50% oil saturation, and a "sand" section 5 ft thick, the areal extent of the structure would have to be more than 11 million square ft, while a domal structure would have a diameter of about 3,800 ft.

The above examples may be used as standards in determining the dimensions of some structures of interest.

The following discussion is based on the premise that the original magnetic data were obtained at the minimum level of safe flying with the maximum economic flight line spacing.

The Marmora area of Ontario, Canada was flown by Aero Service Corporation for the Geophysics Division, Geological Survey of Canada, Department of Mines and Technical Surveys. The area is located 1¼ miles southeast of the town of Marmora, and 120 miles northeast of Toronto. Since the prospect is now being developed as an iron mine by the Bethlehem Steel Company, it should serve to illustrate the practical importance of the choice of line spacing.

GEOLOGY

The Marmora area is located in a zone of Paleozoic limestone outcrops which locally cover the pre-Cambrian sediments of the Grenville. To the west of this local area is the pre-Cambrian basic igneous mass of the Crow Lake structure. The Grenville series are metamorphosed igneous and sedimentary rocks which have been intruded by syenite and gabbro (Garland, 1951).

Diamond drilling in the area has shown the limestone to be approximately 120 feet thick. The ore mass underlying this cap is 2,400 ft long and a maximum

of 500 ft wide, and its vertical extent is greater than 500 ft. The ore zone is a complex of magnetite, skarn, and syenite "shoots" which strikes northwest-southeast, and dips to the southwest 70° to 80°. The ore averages about $37\frac{1}{2}$ percent iron, for an open-pit tonnage of approximately 20 million tons (Anon., 1953).

AIRBORNE MAGNETOMETER DATA AT VARIOUS FLIGHT LINE SPACINGS

The original magnetic data from the Marmora were obtained on north-south lines flown at a mean terrain clearance of 500 ft. The spacing between flight lines

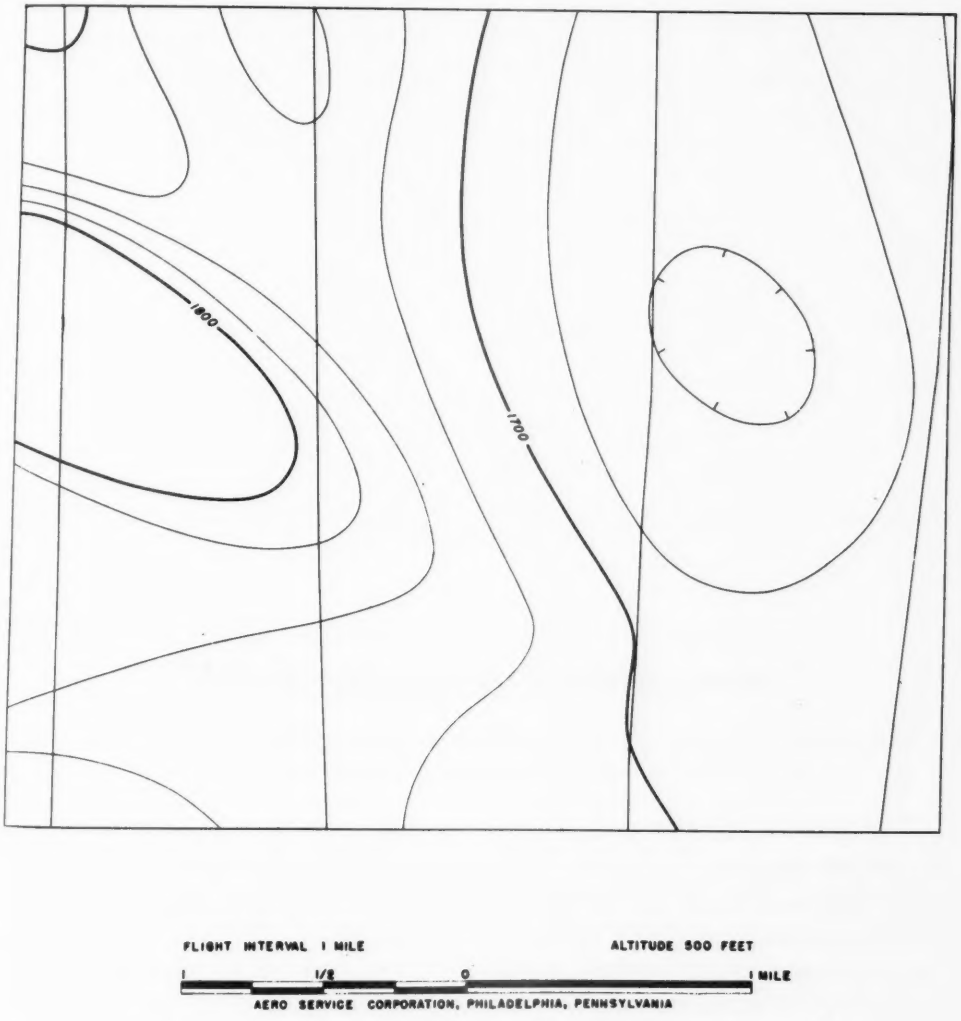

FIG. 1. Airborne magnetometer map over the Marmora anomaly for 1 mile spacing of flight lines.

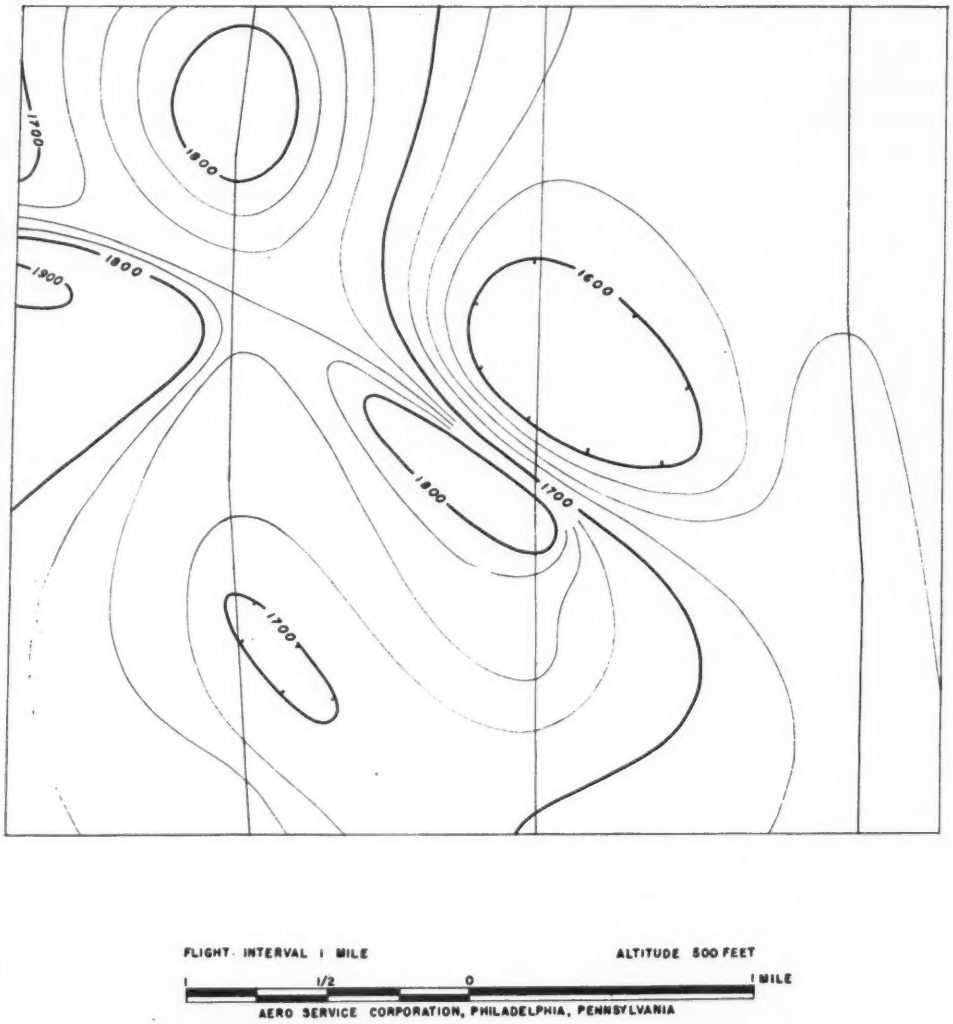

FIG. 2. Airborne magnetometer map over the Marmora anomaly for 1 mile spacing, with a $\frac{1}{4}$ mile shift westward of flight lines from positions shown in Figure 1.

was $\frac{1}{4}$ mile. The partial results of this survey are shown on the map of the Department of Mines and Technical Surveys, Geological Survey of Canada, labeled AEROMAGNETIC, CAMPBELLFORD Sheet No. 31 C/5.

The maps of total magnetic intensity observed at a flight level of 500 ft are presented in such a sequence that the coarsest flight line spacings are shown first. Figures within each group, representing a constant spacing, show the effects of shifting the flight lines to the west.

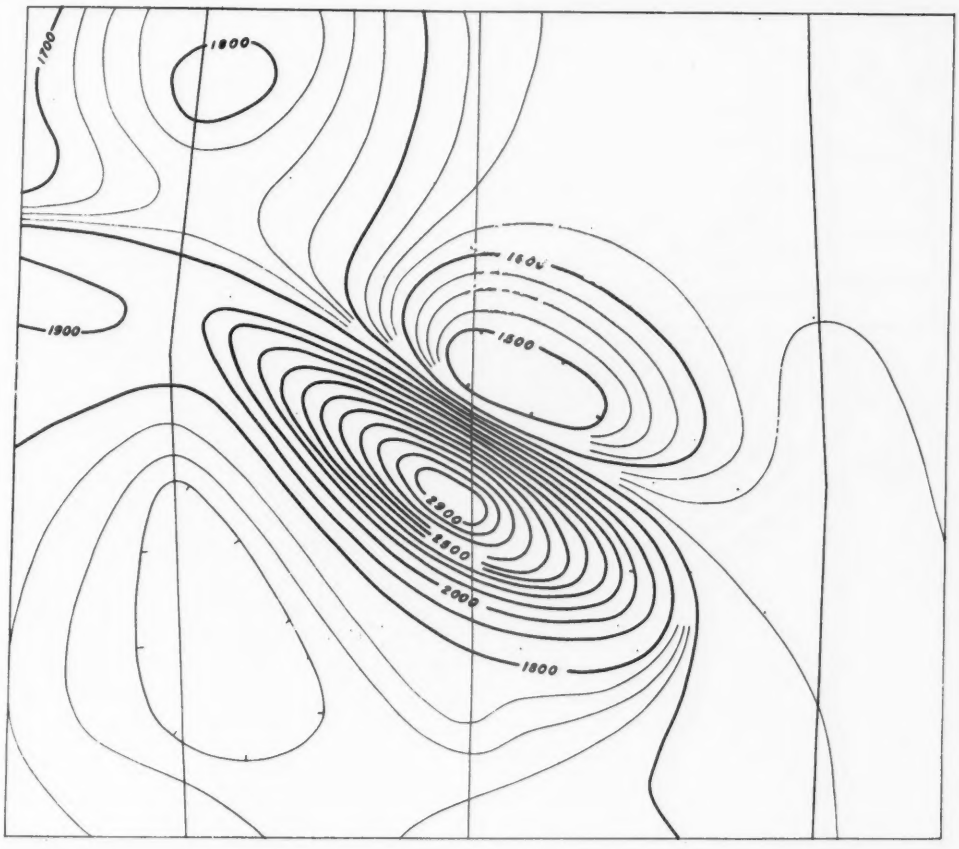

FIG. 3. Airborne magnetometer map over the Marmora anomaly for 1 mile spacing, with a $\frac{1}{4}$ mile shift westward of flight lines from positions shown in Figure 2.

One-Mile Spacing

Figure 1 shows the magnitude of the local anomaly for this distribution of flight lines to be 100 gammas. Two maxima are observed, one in the west central portion and one in the northwest corner of the area. These would be of little interest in a survey for magnetite concentrations, since they are caused by shallow sources, and the magnetic anomaly of 50 to 75 gammas is due to a minor variation in the magnetic content of the rock.

Figure 2 shows the map obtained when the control lines are shifted $\frac{1}{4}$ mile to

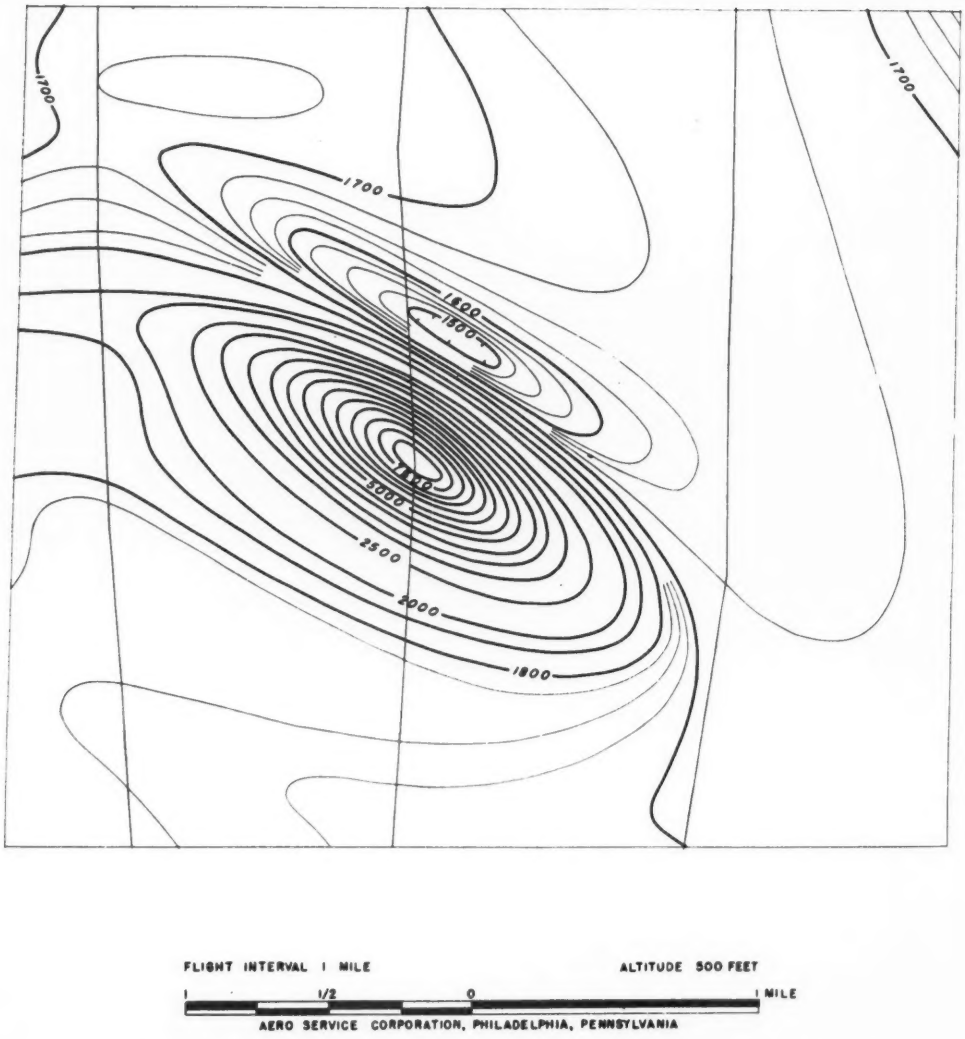

FIG. 4. Airborne magnetometer map over the Marmora anomaly for 1 mile spacing, with a $\frac{1}{4}$ mile shift westward of flight lines from positions shown in Figure 3.

the west with respect to those flown for Figure 1. An entirely different distribution of the anomalies is obtained. A relatively strong northwest-southeast trend is mapped, and high closures are formed in the center of the area, and in the northwestern part. The relatively strong north gradient, and the associated negative axis, may be interpreted as the contact zone between two rocks or as a possible fault line. The cause of these anomalies is shallow, as indicated by the limited sharp gradients. The magnetic anomaly of the central high closure has a magnitude of 120–140 gammas. Considering the shallow source, limited areal extent, and

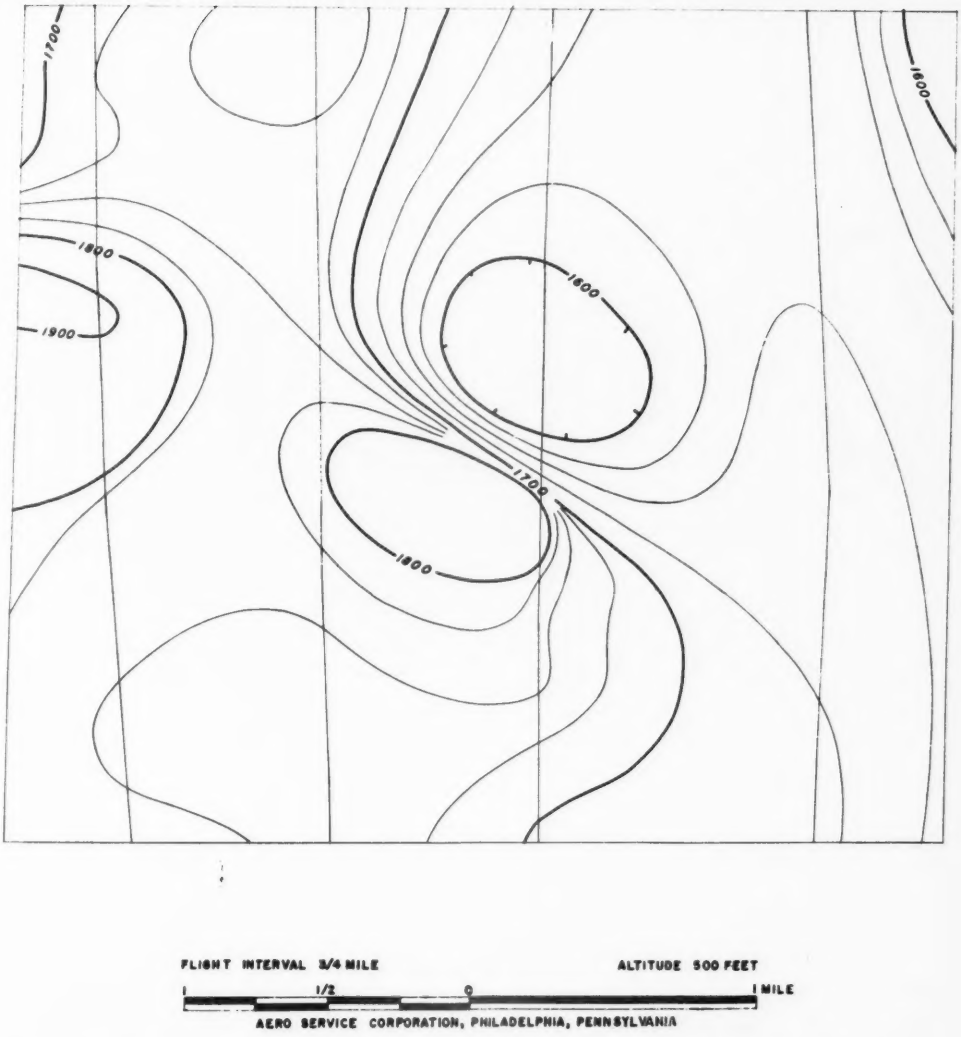

FIG. 5. Airborne magnetometer map over the Marmora anomaly for $\frac{3}{4}$ mile spacing of flight lines.

small magnitude magnetic anomaly, the area would not be of interest in an iron ore survey of the type which was carried on here.

Figure 3 shows the effect of a $\frac{1}{4}$ mile westward shift of the flight lines. The predominant anomaly is located in the center of the mapped area; it is an 1,100-gamma positive anomaly which is flanked to the north by a 300-gamma negative anomaly. Depth estimates from this feature place its source 700 to 800 ft subflight, with the mass causing the anomaly having a maximum length of 7,000 ft and a width of 1,500 ft. The susceptibility contrast of the source based on the above values would be 0.014 cgs. units, representing a concentration of 12 to 14

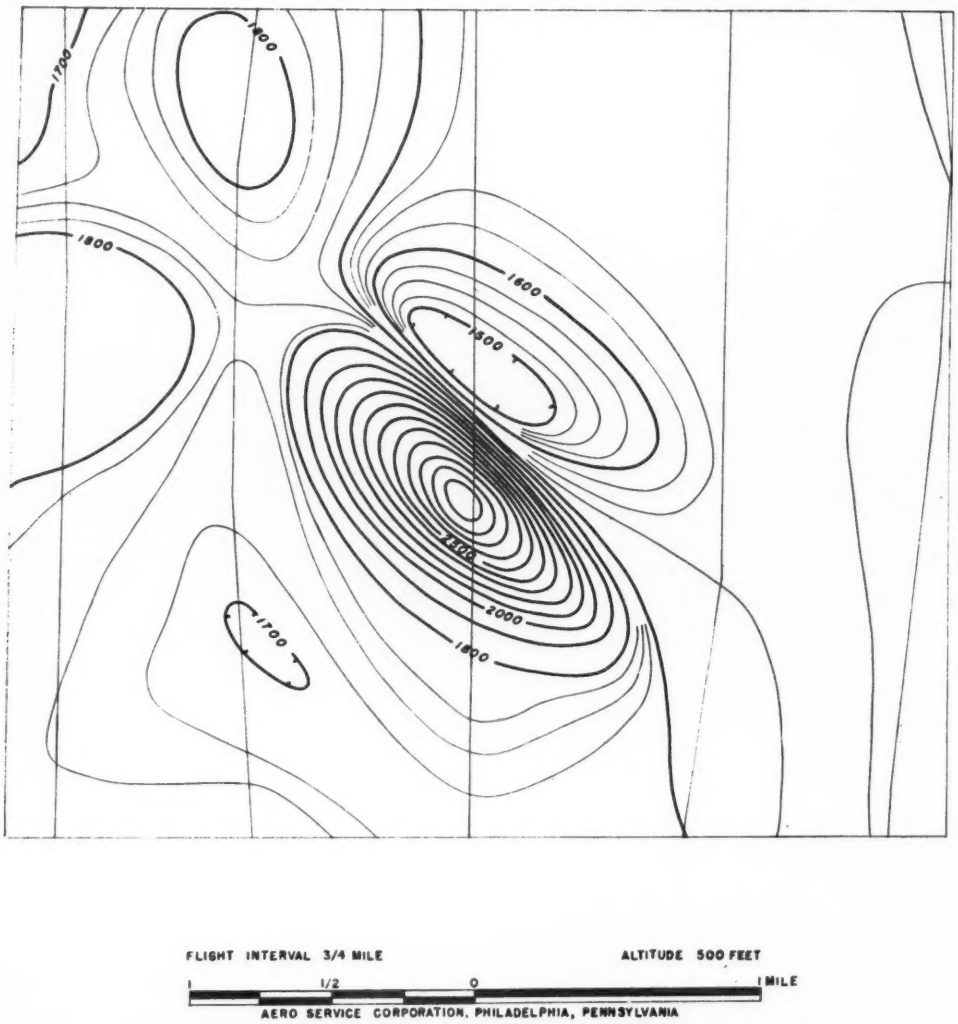

FIG. 6. Airborne magnetometer map over the Marmora anomaly for $\frac{3}{4}$ mile spacing, with a $\frac{1}{4}$ mile shift westward of flight lines from positions shown in Figure 5.

percent magnetite by volume. In view of this concentration it is doubtful that this feature would arouse any interest.

Figure 4 has its control lines shifted $\frac{1}{4}$ mile to the west of the lines shown on Figure 3. The mapped area is dominated by the 6,000-gamma closure. The estimated depth to the source of the anomaly is of the order of 800 ft sub-flight. The areal extent of the source is the same as that given above (1,500 ft by 7,000 ft). Based on these values, the susceptibility of the mass is found to be 0.087 cgs units, which is equivalent to a concentration of from 40 to 55 percent magnetite

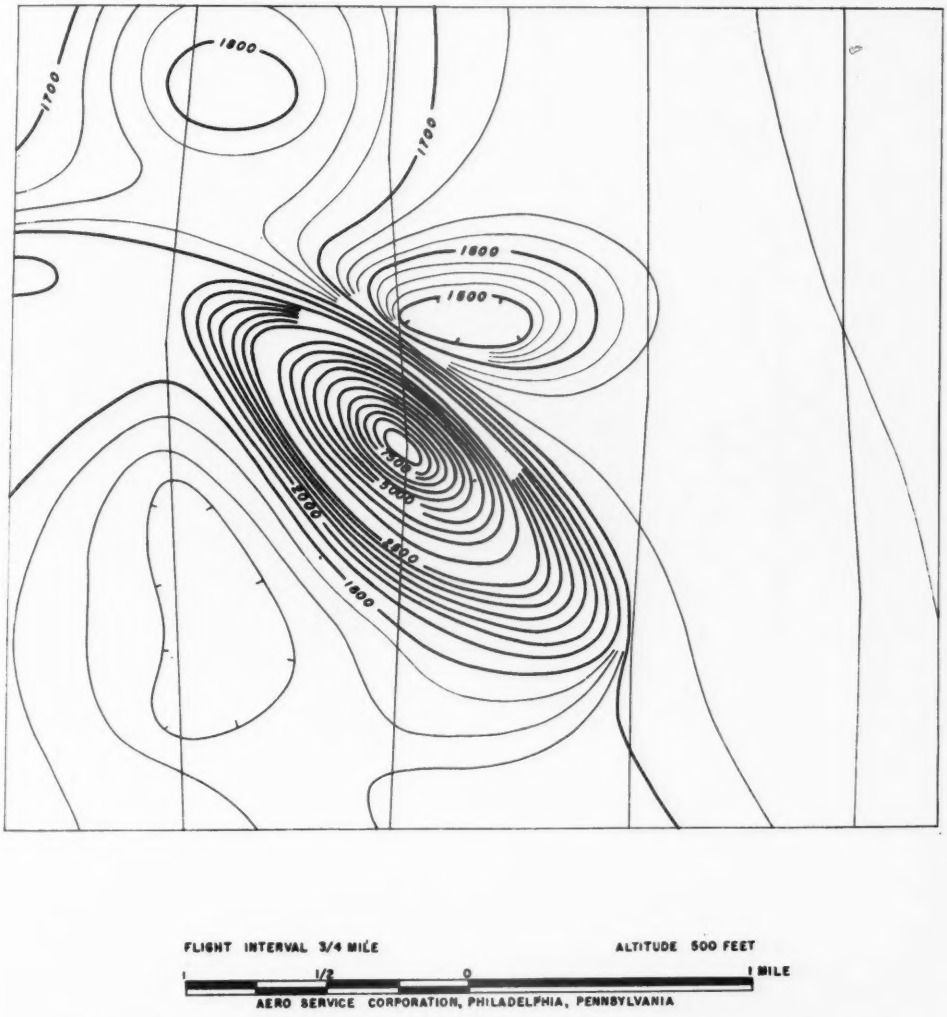

FIG. 7. Airborne magnetometer map over the Marmora anomaly for $\frac{3}{4}$ mile spacing, with a $\frac{1}{4}$ mile shift westward of flight lines from positions shown in Figure 6.

by volume. This computed susceptibility would represent an ore-grade concentration.

Three-quarter Mile Spacing

The contours of Figure 5, based on a flight-line spacing of $\frac{3}{4}$ mile, are similar to the results mapped on Figure 2 for the 1-mile spacing. However, the decrease in the line spacing has tended to reduce or confine the extent of the anomaly. While the closer line spacing has reduced the areas of the anomalies, some of the detail which is observed on Figure 2, such as the low closure to the southwest of

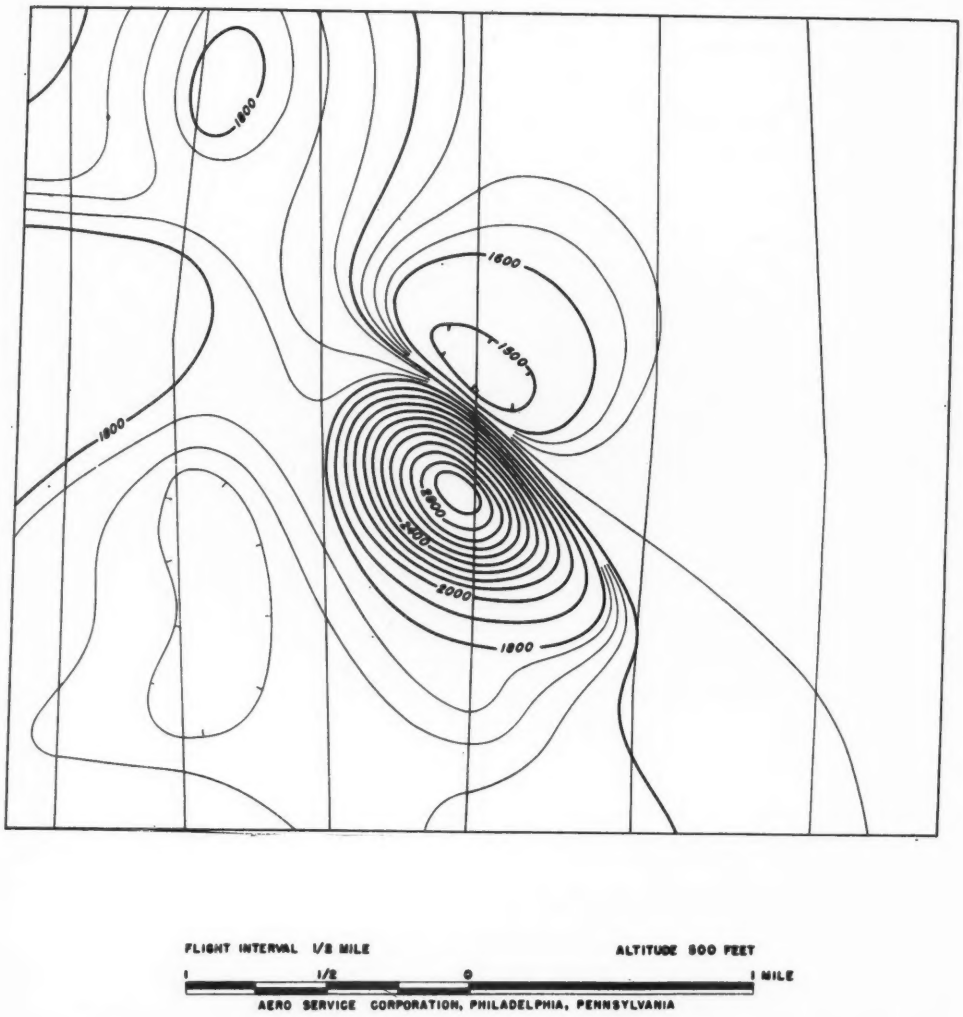

FIG. 8. Airborne magnetometer map over the Marmora anomaly for ½ mile spacing of flight lines.

the central high and the high closure in the northwest corner, is not mapped because of the flight-line locations. Except as a possible indication of a fault or contact zone, which might be mineralized, this anomaly would not normally be investigated further for iron ore because of the low concentration of magnetite necessary to account for the anomaly.

Figure 6 shows contours based on the data mapped using lines located ¼ mile west of those used for Figure 5. The major anomaly is similar to that shown in Figure 3 of the one-mile spacing. The major anomalies of these two figures

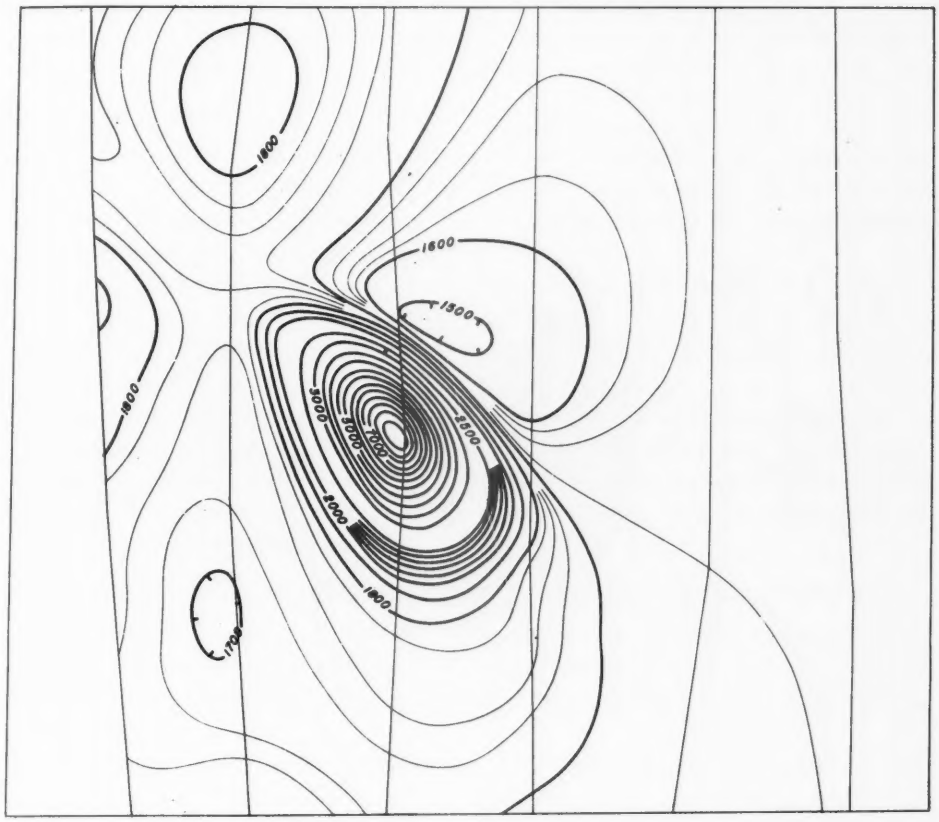

FIG. 9. Airborne magnetometer map over the Marmora anomaly for ½ mile spacing, with a ¼ mile shift westward of flight lines from positions shown in Figure 8.

are the same, but the anomaly lengths are reduced by the closer control-line spacing, and additional detail is revealed. The interpretation of this feature would be the same as for Figure 3.

Figure 7 shows the results of using the control lines ¼ mile to the west of those used for Figure 6. The results of these lines of control are similar to those mapped on Figure 4, and the interpretation would be similar, but with an up-grading of the apparent magnetite content of the source as a result of the increased suscepti-

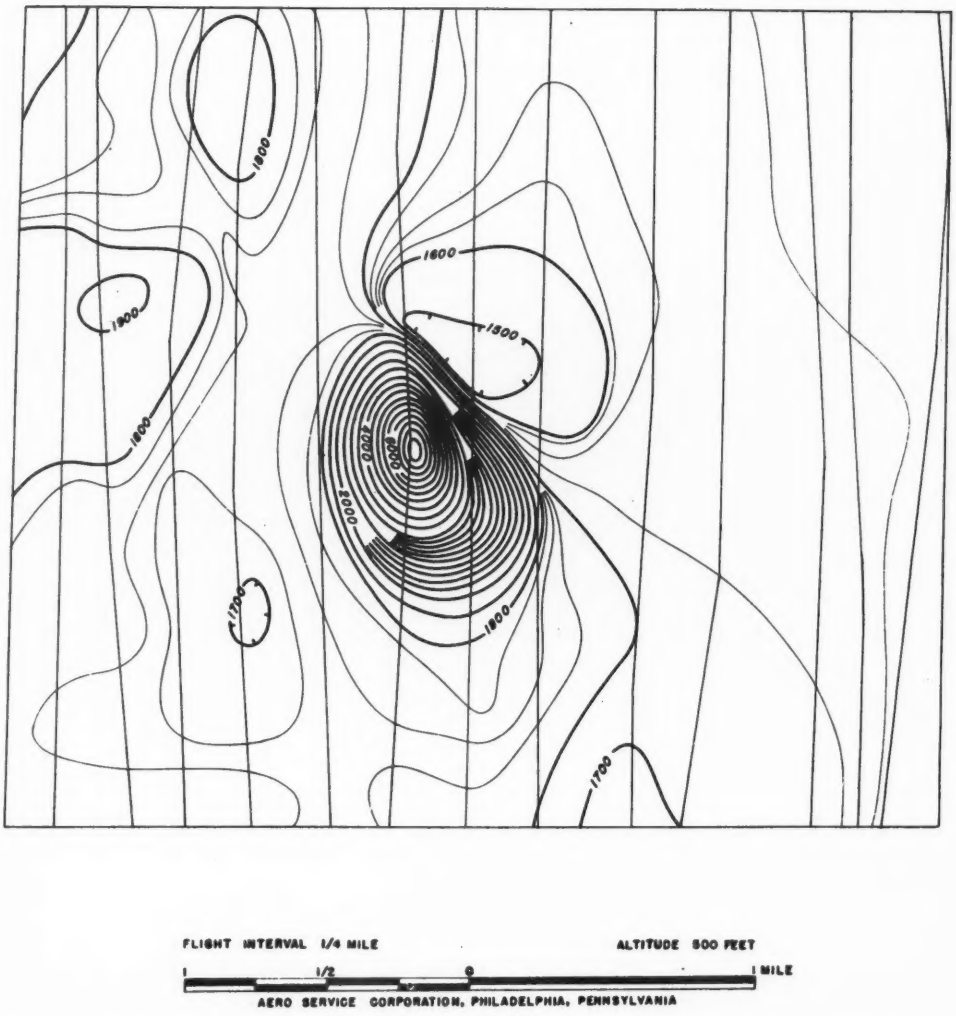

FIG. 10. Airborne magnetometer map over the Marmora anomaly for ¼ mile spacing of flight lines.

bility value computed on the basis of the decreased areal extent of the apparent cause of the anomaly.

One-half Mile Spacing

Figures 8 and 9 show the results of a ½ mile spacing of the lines of control. Figure 8 shows an anomaly of 1,100 gammas, but Figure 9, using control lines ¼ mile to the west of those for Figure 8, shows an anomaly of more than 7,000 gammas. While the anomaly length is confined to a distance twice the control line spacing on both maps, the true apex of the anomaly is better indicated on the

map of Figure 9. It appears to be located 300 ft to the west of the flight line falling closest to its position.

One-quarter Mile Spacing

Figure 10 shows the airborne magnetometer survey results for $\frac{1}{4}$-mile spacing. Essentially, the mapped contours are similar to those observed on Figure 9, except for the addition of detail and the confinement of the anomaly within a northwest-southeast distance interval of $\frac{3}{4}$ mile.

The depth determination from the mapped data shows the source of the anomaly to be 600 to 700 ft below the flight level, which was 500 ft above the terrain. This compares favorably with the ore body's depth of 120–150 ft sub-surface as found by drilling.

The source of the anomaly would be computed to be 2,500 ft long and 750 to 1,000 ft wide. The value of the length as interpreted from the magnetic data compares favorably with that found by drilling, but the values of the width are too high. However, more detailed analysis of the magnetic data would probably yield better agreement.

DETERMINATION OF OPTIMUM LINE SPACING FOR GEOPHYSICAL SURVEYS

In the planning of a geophysical program it is necessary to determine the spacing of survey lines to be used. This spacing should be such as to insure a high probability of observing the geophysical anomaly from the body having economic interest.

The geophysicist, upon considering the dimensions of the structure or body which is being sought, may determine the areal extent of the geophysical anomaly which would be caused by the body. For seismic surveys the areal extent of the structure and of its seismic anomaly would be the same regardless of the distance between the structure and the plane of observation. However, in the case of gravity, magnetic, and, to a certain extent, electrical and radioactive surveys, the areal extent of the geophysical anomaly depends on the distance between the plane of observation and the body being sought as well as on the areal extent of the body itself.

The geological conditions encountered in petroleum surveys present different problems from those encountered in mineral surveys. In petroleum surveys by potential methods, the thickness of the sedimentary section controls the distance between the plane of observation and the source of the geophysical anomaly.

The problem to be solved is to find the probability, which can not exceed unity, of detecting a geophysical anomaly of the required minimum dimensions with a given line spacing. This is a problem in continuous geometric probabilities for which the mathematics has been worked out by Czuber (1908).

For a given circular anomaly whose diameter is D, which is less than the line spacing S, the probability of a line crossing the anomaly would be the ratio

$$P = D/S. \qquad (1)$$

For the case of elongate anomalies of length L, randomly distributed over the area of the survey, where the line spacing S is greater than L, the probability of crossing such features would be

$$P = 2L/\pi S, \tag{2}$$

which is the solution of Buffon's problem.

For randomly distributed features having a length L, greater than the line spacing S, the probability of crossing such features would be

$$P = \frac{2L}{\pi S}(1 - \sin\theta_0) + \frac{2\theta_0}{\pi}, \tag{2a}$$

where $\cos\theta_0 = S/L$. When $S/L = 1$, equation (2a) reduces to equation (2).

For the case of randomly distributed rectangular anomalies of length L and width W, whose diagonal is less than the line spacing S, the probability of crossing such features would be

$$P = 2(L + W)/\pi S. \tag{3}$$

For irregularly shaped anomalies of perimeter A, the probability of crossing would be

$$P = A/\pi S. \tag{3a}$$

For grid spacings of S and $T > S$, where $L < S$, the probability of crossing randomly-distributed elongate features would be

$$P = \frac{2L(S + T) - L^2}{\pi ST} \tag{4}$$

and for circular anomalies of diameter D less than the smaller side of the grid, the probability of crossing the randomly distributed features would be:

$$P = \frac{D(S + T - \pi D)}{ST}. \tag{5}$$

In the case of Marmora, it may be shown, on the basis of these equations, that the probability of locating ore bodies of such dimensions for the 1-mile flight line spacing would be 0.350; for the $\frac{3}{4}$ mile spacing it would be 0.625; for the half-mile spacing it would be 0.700; and for the $\frac{1}{4}$ mile spacing it would be 0.900.

CONCLUSIONS

This study of the Marmora, Ontario airborne magnetometer survey has illustrated how it is possible to miss an anomaly caused by an economic source through insufficiently close flight line spacing. Equations have been given for the determination of the probability of locating an anomaly of given dimensions with a chosen line spacing or grid.

ACKNOWLEDGMENTS

The writer wishes to thank Mr. Virgil Kauffman, President of Aero Service Corporation, for permission to publish this paper, and the members of the Aero Service Corporation's Magnetic Data Compilation Division for the recompilation of the data and the drafting of the figures.

Grateful acknowledgment is given to Mr. George Hanson, Director of the Department of Mines and Technical Surveys of the Geological Survey of Canada, for granting permission to use the original compilation shown on Figure 10 from the Survey's Campbellford Sheet 31 C/5, and the recompilations from this map.

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GEOPHYSICS, VOL. XX, NO. 4 (OCTOBER, 1955), PP. 886–912, 16 FIGS.

SOME APPLICATIONS OF GEOPHYSICAL PROSPECTING IN THE UNION OF SOUTH AFRICA*

J. F. ENSLIN†

ABSTRACT

The major application of geophysical prospecting in the Union of South Africa is in determining locations for drilling water wells. Four principal approaches are employed: 1. Permeable contact zones between igneous intrusions and sedimentary rocks are sought by magnetic surveys. 2. Basins of decomposition are sought by the resistivity method. 3. Narrow water-bearing fissures and fault zones are located by an electromagnetic method. 4. The water-bearing and water-yielding properties of rocks are determined from their computed resistivities.

The interpretation of resistivity depth probe curves is based on an empirical method which corrects for lateral effects.

Another important application of geophysical prospecting in the Union is in gold-mining. Gravitational and magnetic surveys have been widely used in the search for auriferous reefs in the Witwaterstand system which are concealed by a deep cover of younger rocks.

Resistivity, electromagnetic, gravitational, and seismic methods have been applied to problems of engineering geology, including the delineation of areas in dolomite where sinkholes may occur.

INTRODUCTION

The following factors have largely controlled the application and development of geophysical prospecting in the Union of South Africa:

(a) The probability that any oil pools will be discovered in the Union is remote, and the areas that still merit prospecting for oil are limited. Geophysical prospecting for oil, which accounts for more than 98 percent of all activity in exploration geophysics (Eckhardt, 1953), is therefore of minor importance in South Africa.

(b) The Witwatersrand system, with its very important gold-bearing reefs, can be traced under the cover of more recent formations by magnetic and regional gravitational surveys, and under favorable conditions the position of the subcrop of the reefs and the depth of the cover can be determined.

(c) South Africa is for the most part a semi-arid country, and in over 70 percent of its area the farmers are dependent solely on ground water for domestic purposes and stock. Bore-holes yielding more than 100 Imperial gallons per hour are considered successful for these purposes. The minimum yield for successful bore-holes drilled for irrigation, town or railway supplies, etc., is naturally much higher.

Suitable boring sites are more and more difficult to find; the percentage of failures and the average depth of bore-holes have increased (Fig. 1); and the cost of one watering point, developed by government drilling machine, has more than

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doubled since 1943. The sites for more than 95 percent of the existing 300,000 bore-holes have been selected without the use of geophysics. The search for water has become a major problem in some parts of the country and the most promising solution of the problem in the more difficult areas lies in geophysical surveying.

The objective of this paper is to discuss some of the important applications of geophysical techniques in the Union of South Africa, particularly those with

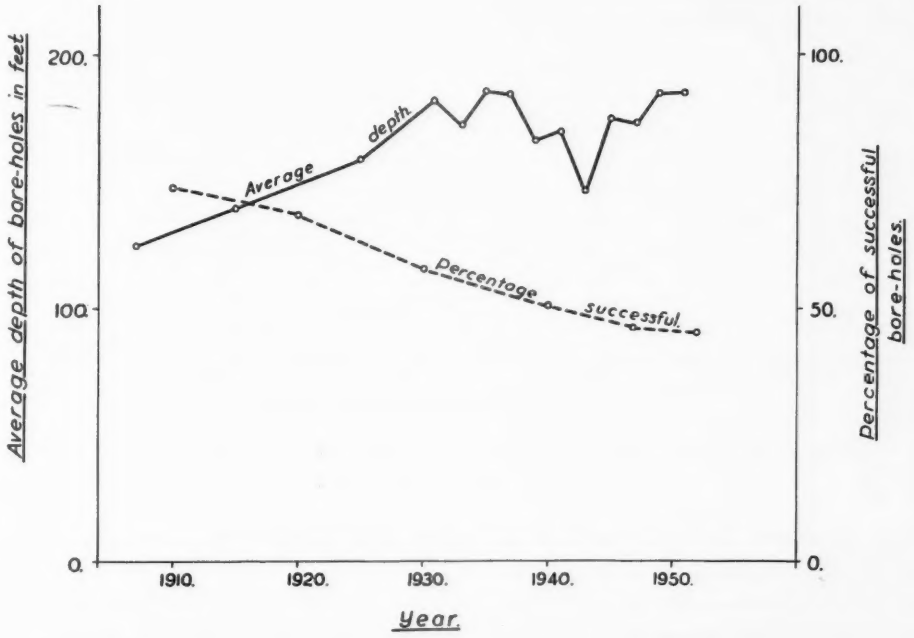


FIG. 1. Percentage of bore-holes which have been successful (yield more than 100 Imp. gallons per hour) and average depth of bore-holes drilled by the Irrigation Department, Union of South Africa, 1907–1952.

which the writer has been actively concerned. A summary of all geophysical prospecting activity in the Union at the present time will not be attempted.

GEOPHYSICAL PROSPECTING FOR GROUND WATER

General

Approximately 10,000 bore-holes are drilled annually for water by about 1,000 boring machines. The Irrigation Department of the Union Government is the largest single "drilling contractor." The Department had 214 drills in the field during the 1952–1953 financial year, and 2,720 bore-holes with a total depth of 449,148 feet, were drilled for water.

The distribution of yield from bore-holes in the Union is given in Figure 2. A total of about 10,000 bore-holes drilled by the Irrigation Department during

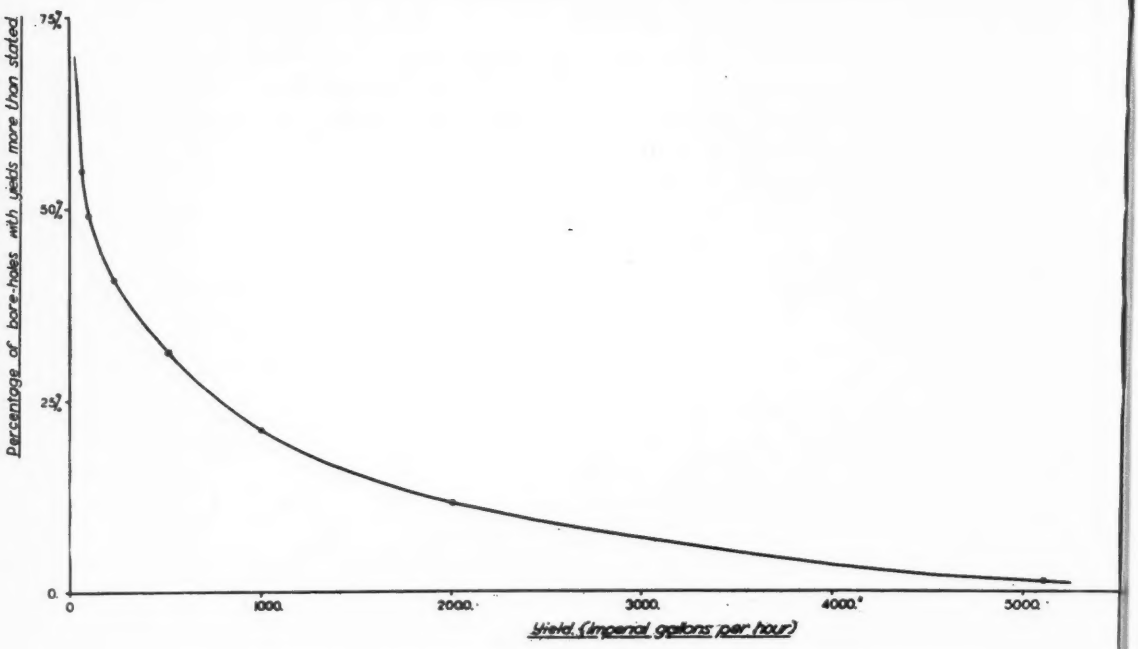


FIG. 2. Distribution of water yields in bore-holes drilled by the Irrigation Department, Union of South Africa, during 1945–1948.

1945–1948 were used in compiling this curve. It is believed that these bore-holes are representative of all drilling carried out in the Union. The relatively low yields of the bore-holes compared with that obtained in other countries result from the fact that highly permeable, superficial, and granular water-bearing formations, which form the major aquifers in the United States of America, are practically non-existent in South Africa.

The majority of bore-holes are drilled in bedrock formations which consist of igneous and sedimentary rocks ranging from pre-Cambrian to Triassic in age.

Geophysical Surveys

The yields of bore-holes in bedrock formations are dependent on the porosity and permeability of the rock. These generally vary a great deal within short distances. The zones of high permeability and porosity in the rocks that serve as aquifers were developed subsequent to the time of their deposition or intrusion and their location cannot in general be predicted from gelogical mapping alone. Even if their presence is suspected, they cannot as a rule be delineated with the accuracy required for the selection of boring sites. In at least 75 percent of the areas investigated for the selection of boring sites, the evidence obtainable from geological indications at surface is insufficient and geophysical exploration must be used for good results.

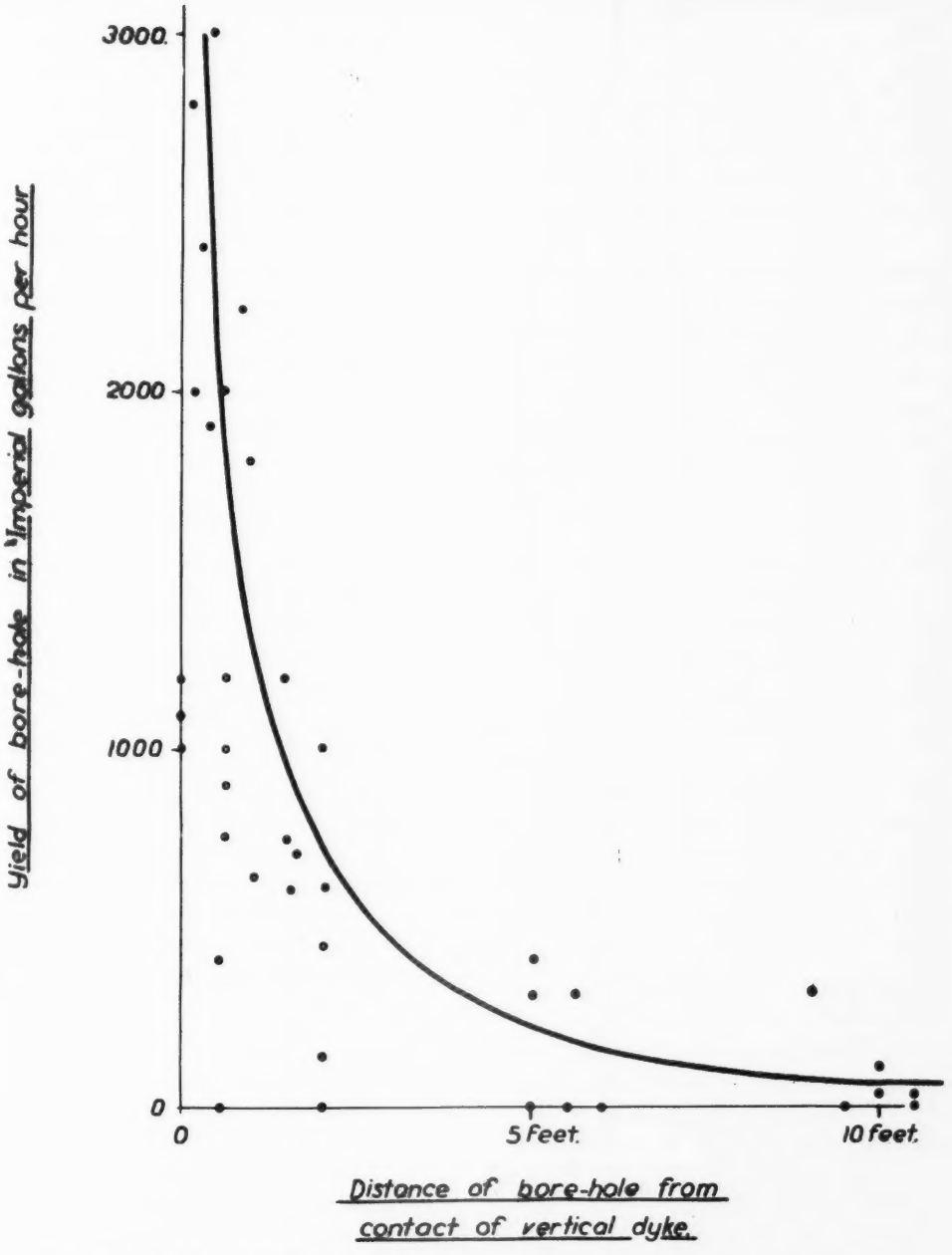


FIG. 3. Yield of bore-holes in Karroo sediments in the Orange Free State as a function of the distance of the bore-holes from contacts of vertical dykes.

The scientific selection of boring sites for water in the Union therefore normally requires a geophysical survey, and for this reason the author envisages a

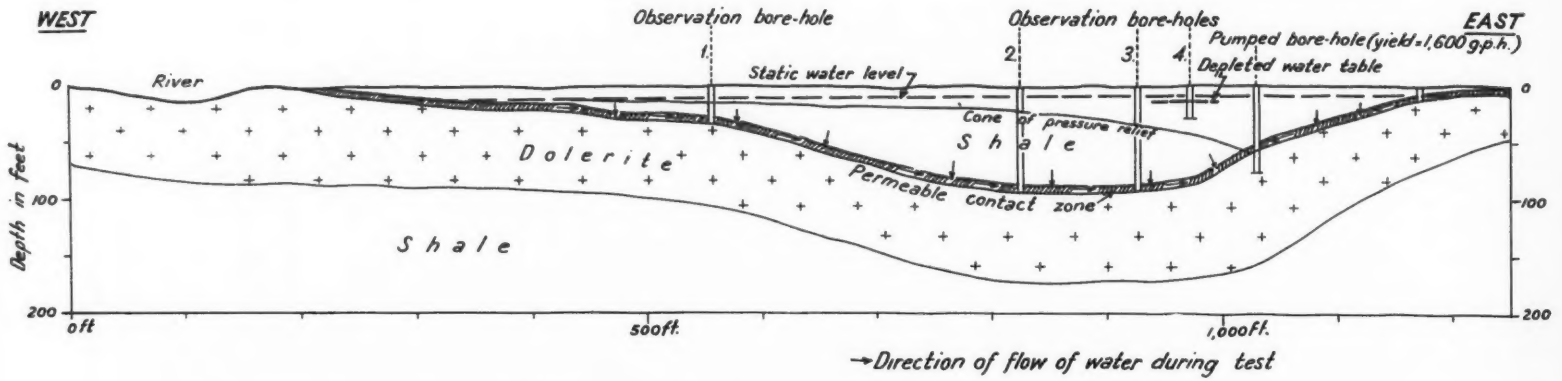


FIG. 4. Section through ground-water basin at Cornelia, Orange Free State, showing (a) static water level, (b) cone of pressure relief and depleted water table at end of 72-hour pump test, and (c) direction of flow of water during test.

great expansion of geophysical activity in the future. Because the ground water occurs under different geological and hydrological conditions, many of the problems have not yet been tackled or solved and many current techniques must be modified—or new techniques developed—in order to discover water under the various conditions that are encountered. It will probably take many years for geophysics to achieve success in solving the ground-water problem in some of the areas of the Union.

Geophysical surveys for the location of ground water differ in several respects from geophysical surveys for minerals and oil. Because of the economics of the situation, a geophysical survey made for the selection of a single drill site should be completed within two or three days at a cost of not more than £30 to £40. To minimize costs and produce flexibility of operations, the field technique is so chosen that interpretations can be readily made in the field. Some of the techniques and their practical applications will be described briefly.

Sedimentary Aquifers at the Contacts of Igneous Intrusions

More than 40 percent of the area of the Union consists of exposures of Karroo sediments of Carboniferous to Triassic age, intruded by a network of dolerite dykes and sills. With the exception of the folded rocks in the Cape Province, the shales, mudstones, and sandstones of the Karroo system are essentially flat-lying and generally have very low permeabilities. Abundant supplies of water are rarely found in these rocks except in the zone of baked rock at the contact of the dolerite intrusion and the sedimentary rocks.

This baked zone seldom exceeds a few inches in width at the contacts of narrow, vertical, or steeply dipping dykes. As these contacts are only roughly planes, a bore-hole drilled within three feet of the contact of a vertical dyke has a very good chance of penetrating the indurated (baked) zone and striking a supply of water. In Figure 3 the yields of bore-holes are plotted against the distances of the bore-holes from vertical dykes.

During pumping operations the water stored in the sediments, which form the ground-water reservoir, slowly percolates into the contact zone, which acts as the aquifer, at all points over its large area, and then flows along the aquifer into the bore-hole. Sub-artesian conditions are thus encountered, and the dip of the contact zone becomes an important factor in determining the yield of the bore-hole. The largest supplies are generally obtained in the vertical contact zones of dykes; good supplies are also found, however, above flat-lying dolerite sheets in the sediments under conditions where the water table is shallow and the sediments have acquired a high permeability due to weathering near the surface.

A section through a basin formed by a dolerite sill at Cornelia is given in Figure 4. A 72-hour pump test was made on one of the bore-holes in the eastern part of the basin. The cone of pressure relief which was formed during the test could be plotted from observations of water levels in bore-holes no. 1 to 3, which were all drilled through the aquifer (the baked sediments above the dolerite) and

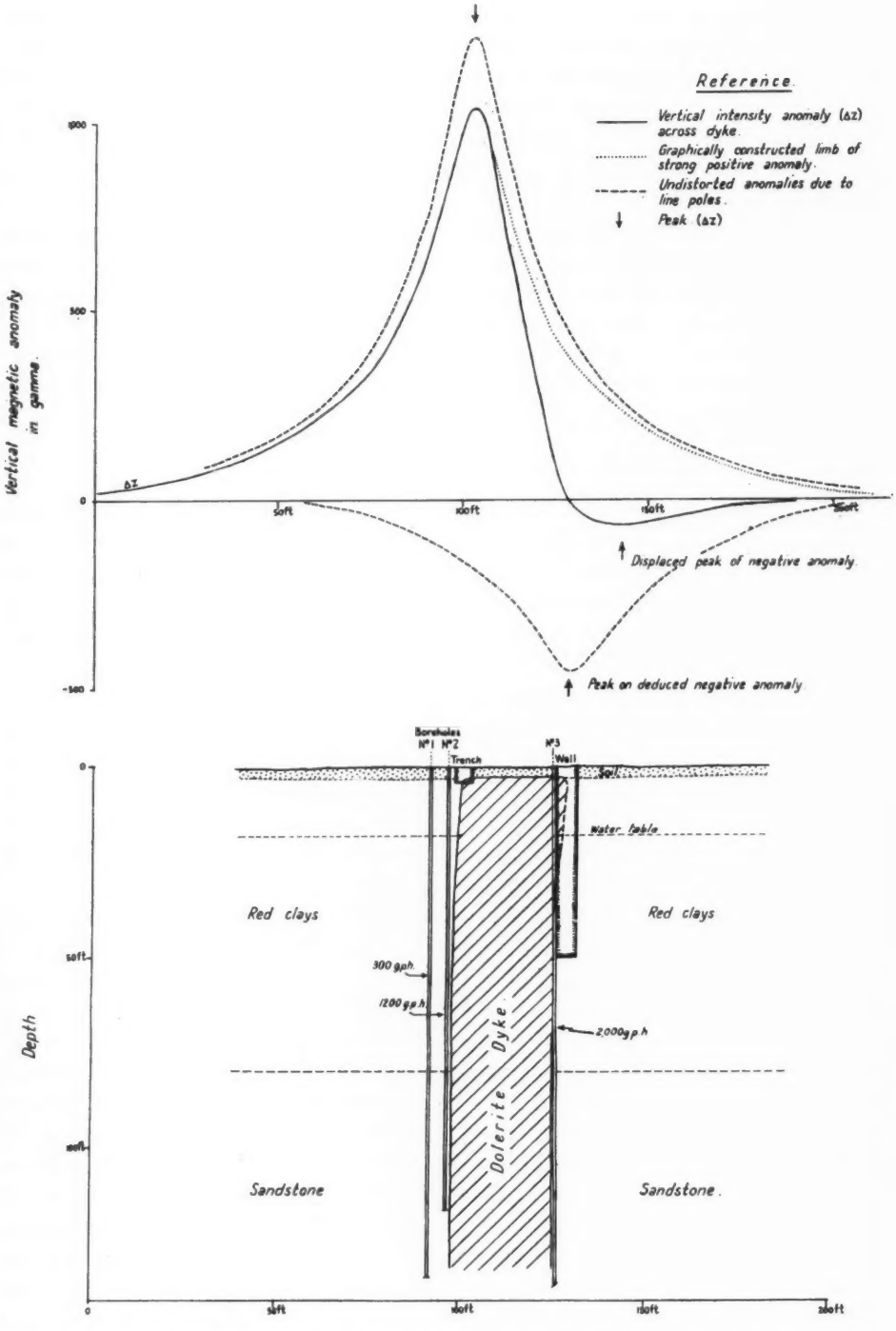


FIG. 5. Interpretation of contacts of dolerite dyke from the vertical intensity magnetic anomaly.

which stopped in solid dolerite. In bore-hole no. 4, which did not reach the aquifer, no corresponding lowering of the water table was observed. In the latter bore-hole the water level dropped only one foot over the 72-hour test; this drop corresponds to the dewatering of the ground-water reservoir during the test.

The slow seepage of the water from the sediments into the baked zone towards the bore-hole from all directions is illustrated by arrows in Figure 4.

There is still a difference of opinion (Weiss and Frost, 1948; Enslin, 1950) as to the best method of tracing the contacts of dykes under cover for the selection of sites for boring. The method devised by the author and now applied with success in routine surveys for the selection of boring sites will be described briefly.

The masking effect of overburden and weathered dyke material, 10 feet to 100 feet deep, causes the dyke to give negligible indications in conventional electrical surveys (either with constant-separation traverses or with depth probing) and the contacts cannot be determined with the required accuracy by such techniques. In many areas, however, the dykes are strongly magnetic and the contacts can be determined with an accuracy of about 3 feet by taking traverses of the vertical magnetic field across the dyke.

The major part of the anomaly across a dyke is due to permanent magnetism of the dyke itself, and the anomaly on any section across the dyke is the resultant of one or more symmetrical negative or positive anomalies due to lines of poles. The peaks of these symmetrical anomalies are vertically above the poles and therefore directly above some point on the dyke. A large percentage of the poles have been found to align themselves along the edges of the dykes. By plotting all peaks obtained on a number of traverses across a dyke, the two outer rows of peaks, which generally are recognizable, should be within a foot or two of the contacts.

The asymmetry of the anomalies is therefore not ascribed to dipping dykes or to induction by the earth's field, but is due to superposition of anomalies with different intensities from individual poles. It has been found that the peak of the smaller symmetrical anomaly, with polarity opposite to that of the larger anomaly, may be displaced by as much as 20 feet from the position directly above the pole, and the contact of a dyke could thus be interpreted incorrectly by plotting displaced peaks. The correct position of the peak can be obtained by the graphical construction shown in Figure 5, as follows.

It is assumed that only the inner limb of the larger (positive or negative) anomaly, which is on the side nearer the smaller (positive or negative) anomaly, has been distorted by the smaller feature. The undistorted symmetrical large anomaly is thus constructed by drawing the inner half of the anomaly symmetrically with the outer half. The difference between the symmetrically-constructed anomaly and the observed anomaly is then assumed to be equal to the smaller anomaly, which is now determined and plotted. The position of the peak of this graphically constructed weaker anomaly is plotted on the map for determining the contact of the dyke.

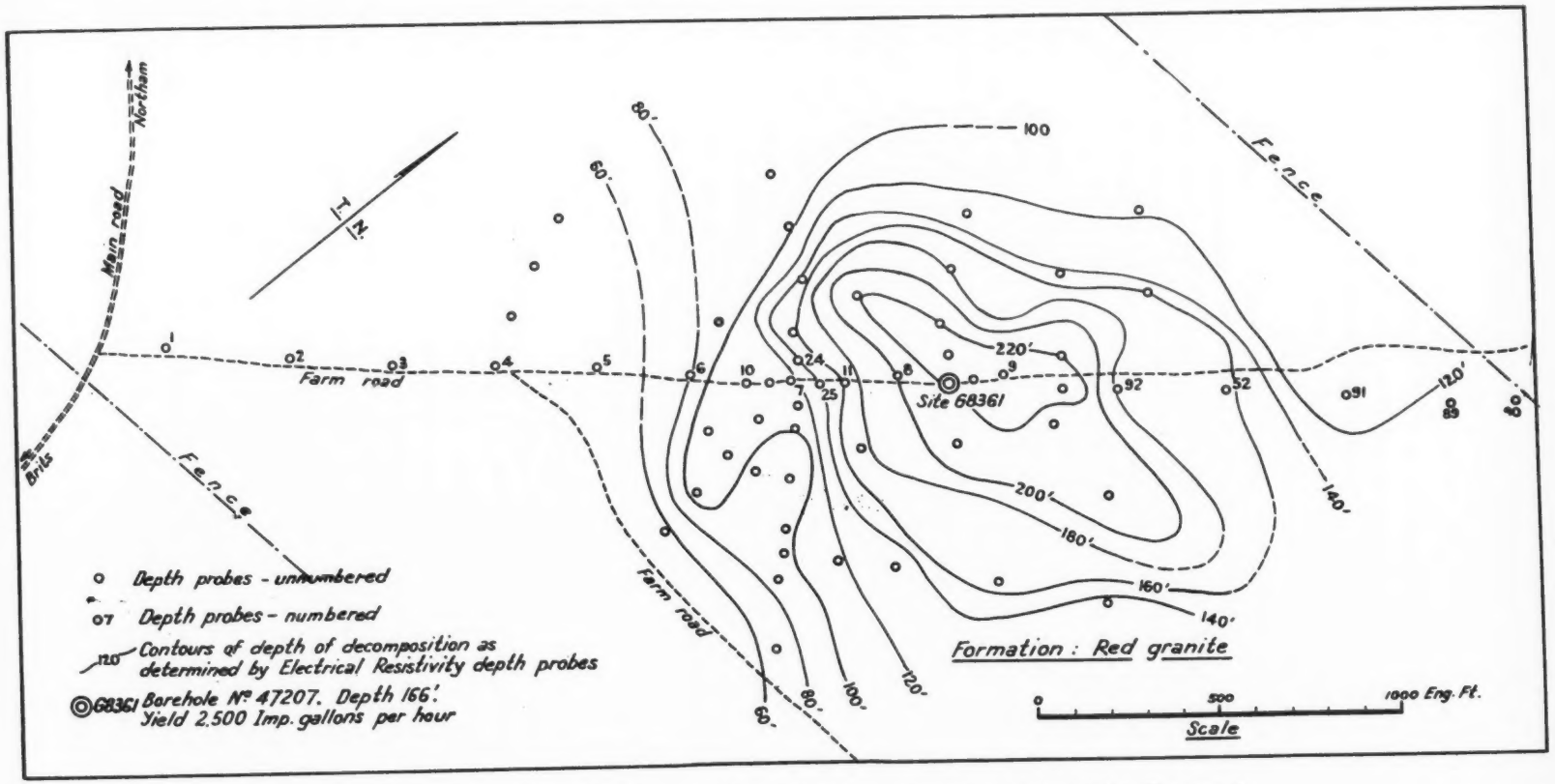


FIG. 6. Contour map of basin of decomposition on the farm Tweerivier 92, Brits district, Transvaal.

Basins of Decomposition in Igneous Rocks

In addition to the scattered diabase and dolerite sills and dykes discussed above, large masses of plutonic and extrusive rocks occur and their outcrops cover 20 percent of the area of the Union. Their importance in ground-water development in the Union is borne out by the fact that 50 percent of all bore-holes drilled by the Irrigation Department are in igneous rocks.

Practically all ground water stored in igneous rocks is stored in weathered rock which tends to vary in depth and lateral extent and which generally forms basin-shaped bodies on a floor of broken-and-solid rock. These basins generally show no surface indications but can readily be delineated by electrical resistivity surveys. Free ground water can be tapped by sinking bore-holes in the deepest parts of the basins, as illustrated in Figures 6 and 7.

Resistivity surveys are perferred to potential-drop-ratio or equipotential-line surveys in order to determine the depth to the floor of the basin as well as to correlate the resistivity with the water-bearing and water-yielding properties of the rocks. For a reconnaissance survey a series of depth probes spaced 200 to 400 yards apart has been found as informative as, and much faster than, constant-separation traverses, which are therefore rarely taken. Under normal conditions in South Africa, where surface resistivity varies within wide ranges over relatively small distances (see Figure 14), constant-separation traverses have been found very deceptive when used to determine the depth of decomposition.

The resistivity instruments used are constructed on the Gish-Rooney principle in the geophysical workshop of the Geological Survey. For routine surveys, the Wenner configuration of electrodes is employed.

Although the decomposed rock forms the major ground-water reservoir for all basins, the movement of ground water varies as water is pumped from bore-holes, and basins can accordingly be divided into two main groups:

Basins in which Free Water Conditions Exist and in which Cones of Depression are Formed when the Water is Pumped.—Granite and the associated acid rocks generally weather to a reasonably permeable granular material. The actual permeability may vary with the depth, but the conditions are generally such as to approach free-water conditions, and the laws of flow under water-table conditions are therefore applicable. The basin of decomposition delineated on Tweerivier 92, Brits district in the Transvaal, is shown in Figure 6, and a geological and resistivity section through it is given in Figure 7. Although bore-hole no. 47207 was stopped in decomposed rock more than 50 feet above the floor of solid rock as interpreted from the depth-probe curve, a yield of 2,500 gallons per hour was obtained (Fig. 8). Nevertheless, it has generally proved advisable to drill until solid, unweathered rock is encountered.

Basins in which Confined Water is Pumped and in which Cones of Pressure Relief are Formed (Fig. 9).—Most basic igneous rocks, unlike granitic ones, decompose to a clayey product with a very low permeability and only the broken and slightly weathered rock of the transition zone at the bottom of the basin is

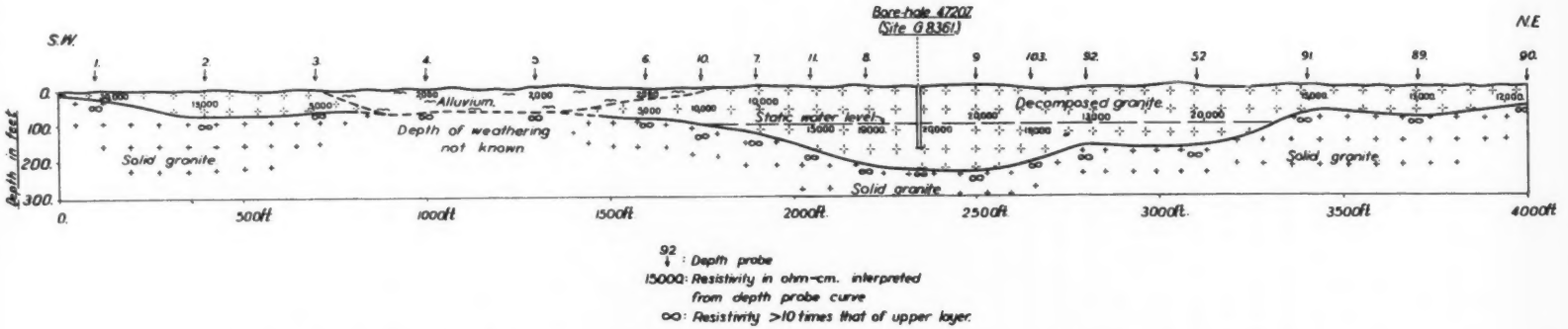


FIG. 7. Geological section showing resistivities through basin of decomposition at Tweerivier, Brits district, Transvaal.

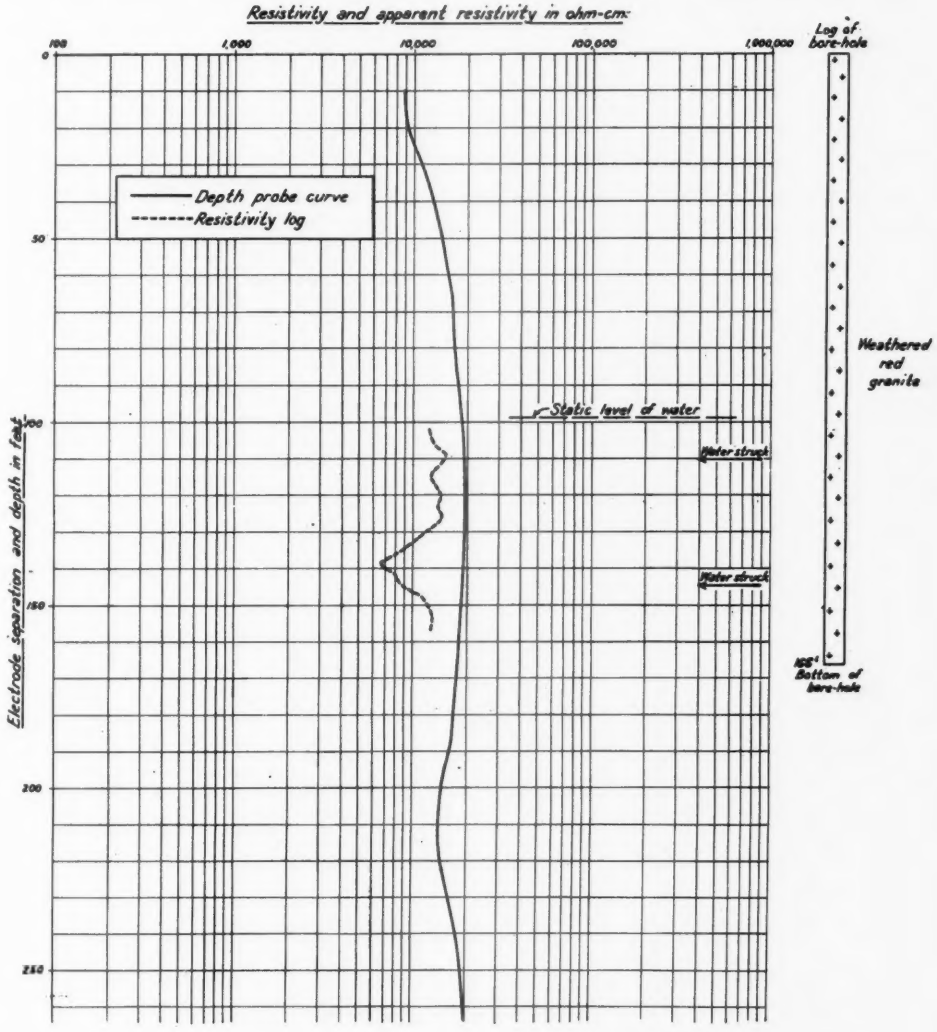


FIG. 8. Resistivity log and depth probe: bore-hole no. 47207, yielding 2,500 gallons per hour, at Tweerivier, Brits district, Transvaal.

permeable. Any bore-hole will be a failure if it is drilled in decomposed rock below the static water level, and stopped before it penetrates this narrow aquifer. If the solid rock in the deeper part of the basin is struck by the drill after the permeable zone has been pierced below water level, a supply of 500 to 3,000 Imperial gallons per hour can normally be expected.

Although the water is stored in the weathered rock, the flow of water into the bore-hole, during pumping operations, is confined to the permeable horizon immediately above the floor of the basin. The yield of the bore-hole is therefore a

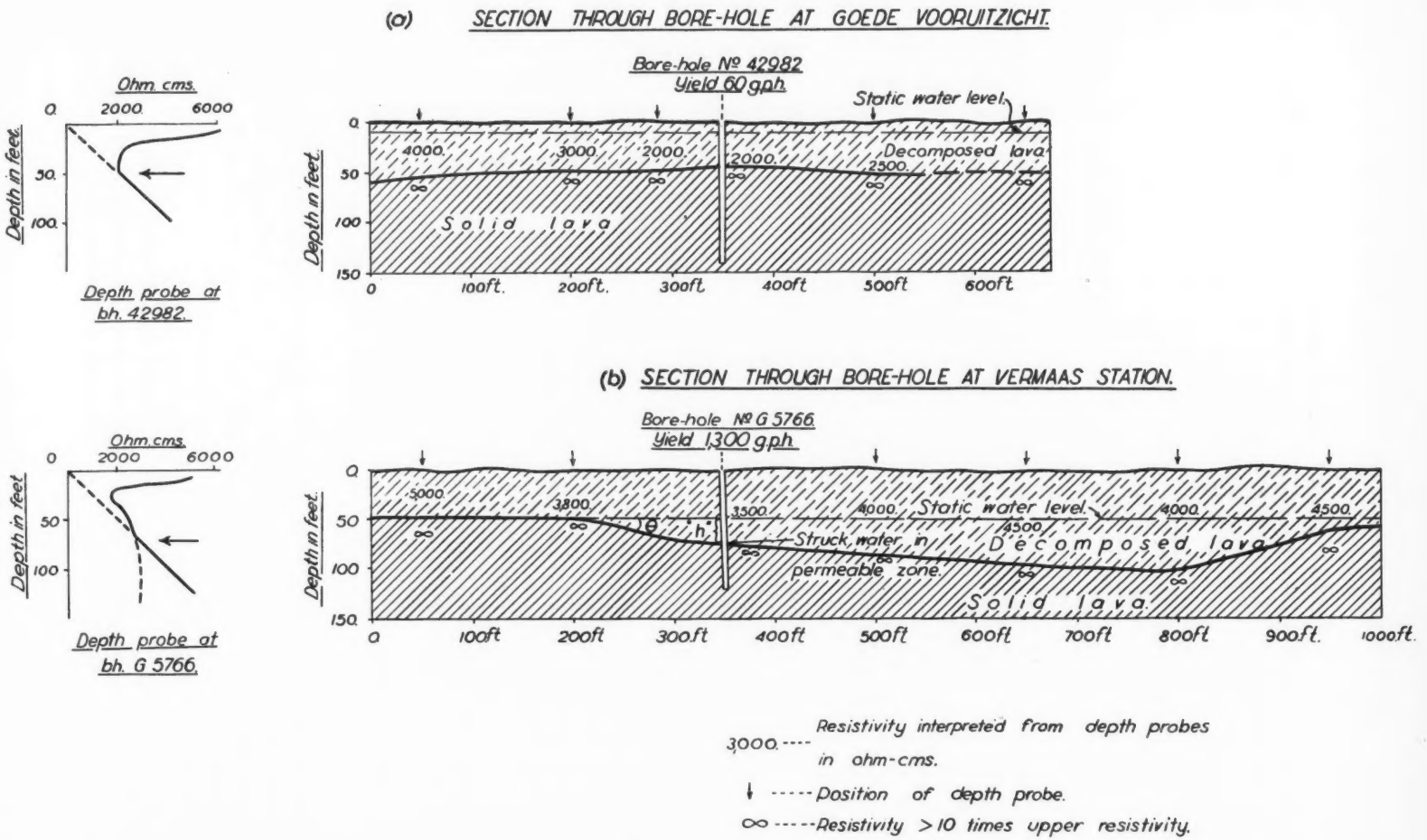


FIG. 9. Comparison of resistivity data indicating (a) unsuccessful and (b) successful bore-holes in andestic lava of the Ventersdorp system in the Western Transvaal.

function of the slope, θ, of this contact zone, as well as the depth, h, of water above the floor of solid rock. During pumping operations a cone of pressure relief is formed.

Interpretation of Depth of Static Water Table

The depth to the static level of the ground water is of primary importance for the selection of suitable boring sites. It has been proved impossible to determine the depth of the water table in bedrock formations by any geophysical method.

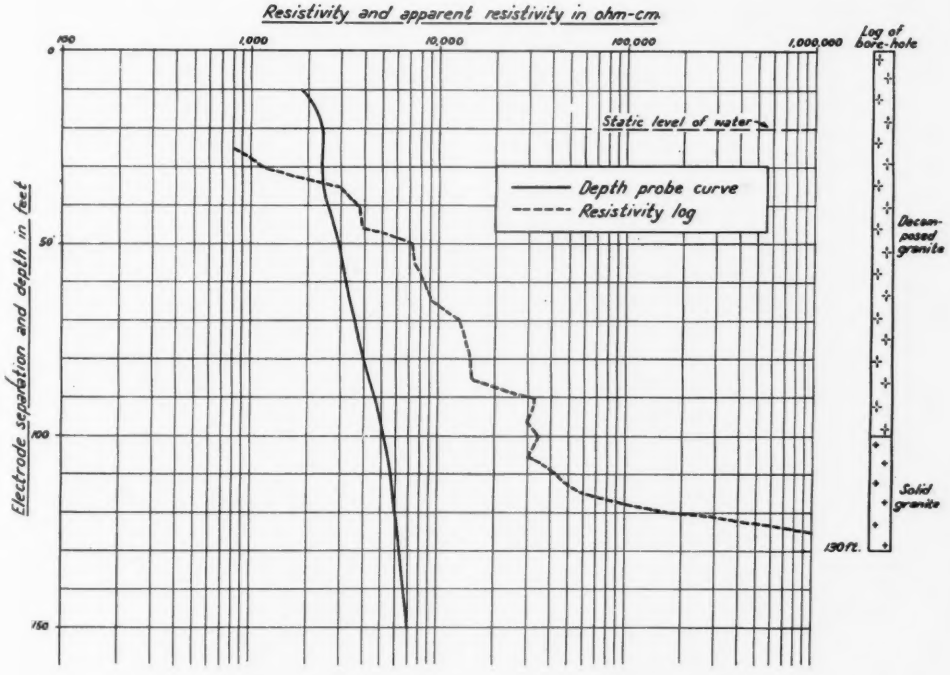


FIG. 10. Resistivity log and depth probe for bore-hole at Palmietfontein 101, Pietersburg district, Northern Transvaal.

The specific retention of the weathered rock is fairly high and, in addition, there is normally a gradual decrease in porosity with depth, with the result that there is generally no sudden increase in percentage moisture content at the water table and, as a consequence, the ground-water level does not demarcate a plane of contrast of the order necessary for detection by surface geophysical measurements. The resistivity log of a typical borehole on Palmietfontein 101, showing the gradual increase in resistivity with depth due to decrease in porosity, is given in Figure 10. The absence of any sharp resistivity change at the water table is clearly shown in the resistivity log of bore-hole G. 1862 on Hartebeespoort 304, Pretoria district, given in Figure 11. The author is, therefore, rather sceptical

about some of the published predictions of depths to water table in bedrock from depth-probe curves.

It is possible to arrive at a fairly accurate estimate of the water level at a given location from the water levels in bore-holes in the vicinity, and by adjusting for topography and other factors.

Fault Planes and Narrow Fracture Zones

Fault planes and fracture zones are important for the selection of boring sites in areas where weathering is shallow, or where large supplies are required for irrigation, towns, or railways. If the faults or fracture zones are 20 feet or more in

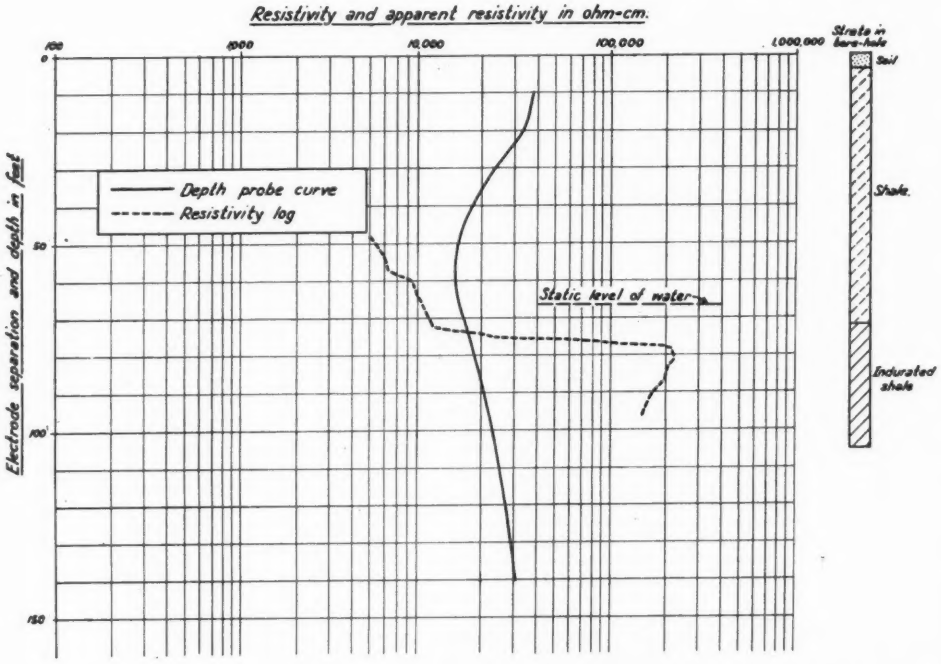


FIG. 11. Resistivity log and depth-probe for bore-hole at Hartebeespoort 304, Pretoria district.

width, such structures can be found in some cases by very detailed resistivity surveys. The majority of these structures, however, will be missed by routine resistivity surveys for ground water, and a large percentage cannot be detected by resistivity surveys at all.

An electromagnetic field technique has been developed for locating and tracing such structures. This technique, described in another paper (Enslin, 1954), can be summed up as follows:

An alternating current of audio-frequency is introduced conductively into the ground. Measurements of the tangential component of the horizontal electro-

magnetic field (called the H_T-field) are taken on concentric circles around this current source. Peaks indicate current concentrations which may be due to fault planes or fracture zones.

An electromagnetic survey is very often carried out supplementary to the resistivity survey in areas where rapid variation in resistivity, both laterally and vertically, tends to complicate and reduce the accuracy of resistivity interpretations. This electromagnetic technique has the advantage over resistivity methods in that the H_T-curves are for all practical purposes not subject to lateral effects and the horizontal position of a linear conducting structure can be determined accurately. Furthermore, fault planes and crushed zones that have been sealed

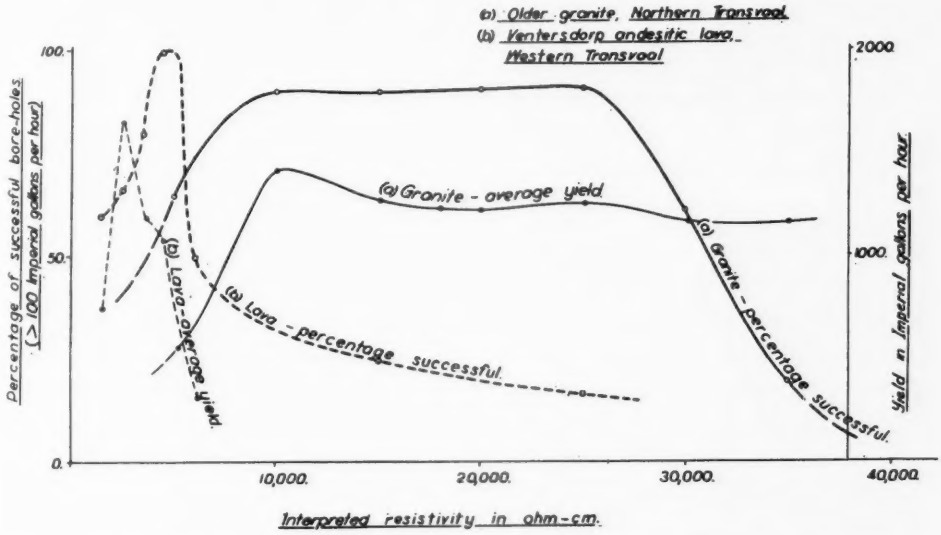


FIG. 12. Yield-resistivity correlation curves, showing percentage of bore-holes successful and average yield of successful bore-holes as a function of interpreted resistivity of formation.

by secondary recrystallization, and therefore rendered unfavorable for locating bore-hole sites, will not produce an H_T-anomaly and can thus be distinguished from water-saturated fractures which form aquifers.

This electromagnetic technique has already been applied with great success in areas where water supplies in narrow aquifers could not previously be located. Flows of more than 10,000 gallons per hour have been observed in some of the bore-holes penetrating such linear structures.

Correlation between Resistivity and Yield

The yields, obtained from bore-holes, of aquifers consisting of weathered igneous or sedimentary rocks can be plotted against the resistivity of the aquifers. The resistivities are interpreted from depth-probe observations at the bore-holes.

The average yield of successful bore-holes and the percentages of successful bore-holes drilled in any particular formation under fairly uniform climatic conditions can thus be determined and plotted as a function of the resistivity (Fig. 12).

These curves, designated as yield-resistivity correlation curves, have been constructed for a number of formations and are used as an aid in estimating the probability of striking a supply of water at any site for which the resistivity of the aquifer has been determined by an electrical survey.

It is assumed that for uniform climatic conditions the salinity of the water in any formation does not vary within wide limits, and that the porosity and per-

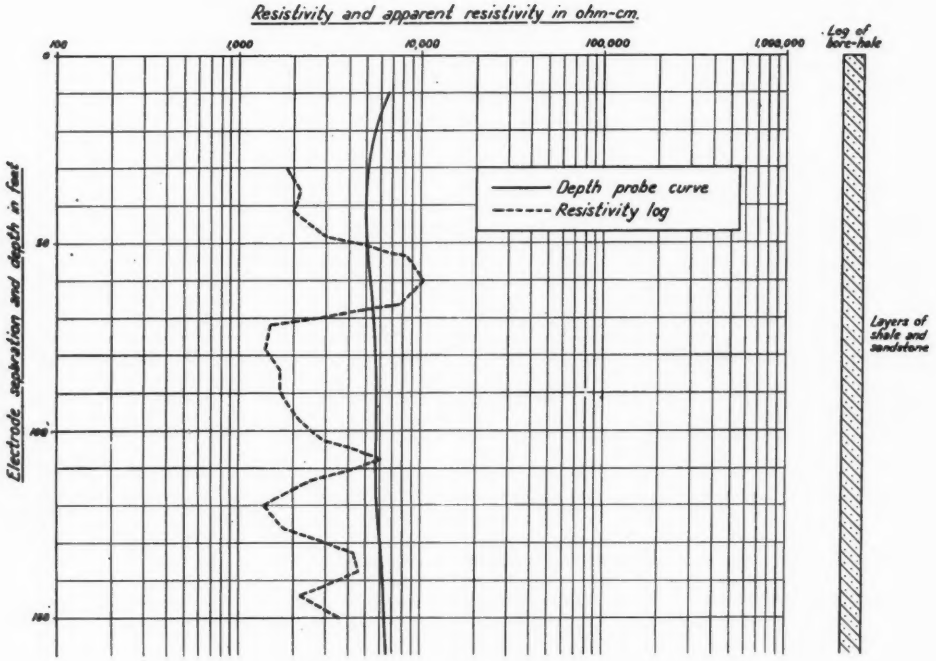


FIG. 13. Resistivity log and depth probe for bore-hole no. 41521, Van Koppe, Harrismith district, Orange Free State.

meability of the aquifer are therefore the main factors determining its resistivity. The yields obtained in fairly homogeneous, porous aquifers, which fall within the low-to-medium-resistivity range for any particular formation, is largely a function of permeability, assuming that the penetrations of the bore-holes below water table in the aquifer do not vary greatly. On the other hand, for the part of the formation which is characterized by high resistivity, any aquifer would be formed by a series of fractures in solid rock, which decrease in number with increase of resistivity. The number of fractures rather than the permeability now becomes the major factor determining the yield.

Interpretation of Depth-Probe Curves

Two factors have determined the method for interpreting the depth-probe curves obtained during routine resistivity surveys in the Union. In most places, the resistivities of geological formations vary rapidly, both vertically and laterally; thus, data can be correctly interpreted by the use of the theory for two, three, or four layers only under exceptional conditions. Figure 13 shows a curve taken over a structure which is indicated by the electrical log to be multi-layered. The curve would normally have been interpreted as being due to an almost homogeneous earth.

The second factor that has governed the choice of interpretation techniques is the fact that the data must be interpreted in the field immediately after observations have been taken. No time is available for detailed methods of interpretation.

All depth probes are taken with the Wenner configuration, oriented parallel to the strike of the formations whenever possible. Differences in resistivities near the electrodes are thus kept to a minimum and interpretation is facilitated. The interpretation of a depth probe is carried out in three stages.

In the first stage the depth probe is interpreted by an empirical method (Figure 14). It is assumed that the subsurface consists of horizontal layers only, with resistivities ρ_1, ρ_2, etc. at depths o to h_1, h_1 to h_2, etc., respectively. The slope of each curve depends on the thicknesses and resistivities of the various layers. If a curve is approaching an asymptote for increasing electrode separations and suddenly changes slope at an electrode separation α_n, the depth to the top of the $(n+1)$st layer is assumed to be $h_n=\alpha_n$. The resistivity ρ_n of the nth layer can be read off the curve if the asymptote $\rho_a=\rho_n$ has been approached closely, or it can be obtained by estimating the way in which the curve would approach its asymptote if the nth layer extended to infinity.

In some instances a segment of the curve will be a straight line which can be extended back through the origin. The electrode separation α_n at which the curve becomes such a straight line is considered to be the depth h_n to the top of a bed of infinite resistivity. By "infinite" is meant a resistivity at least 10 times that of the layer immediately above. In such cases it is impossible to determine the actual resistivity of the lower layer, except under very favorable conditions. This lower layer with "infinite" resistivity is generally solid bedrock, but if the resistivity of the upper layer is very low, the "infinite" resistivity may still be that of decomposed rock. At depth-probe positions nos. 4 and 5 in the section through the basin of decomposition on Tweerivier (Fig. 7), the first layer has a resistivity of 2,000 ohm-cm and the second layer an "infinite" resistivity, which could either be 20,000 ohm-cm, which is the resistivity of decomposed granite, or as high as 10^6 ohm-cm, which is the resistivity of solid granite.

A depth probe is generally considered to be completed as soon as "infinite" resistivity is indicated, and the instruments are moved to the next station. With the type of resistivity instruments used, it is possible to keep the current constant

for the series of electrode separations by means of rheostats in the C-circuit, and "infinite" resistivity is considered to have been obtained when the potential remains constant for two or three consecutive increases of electrode separation.

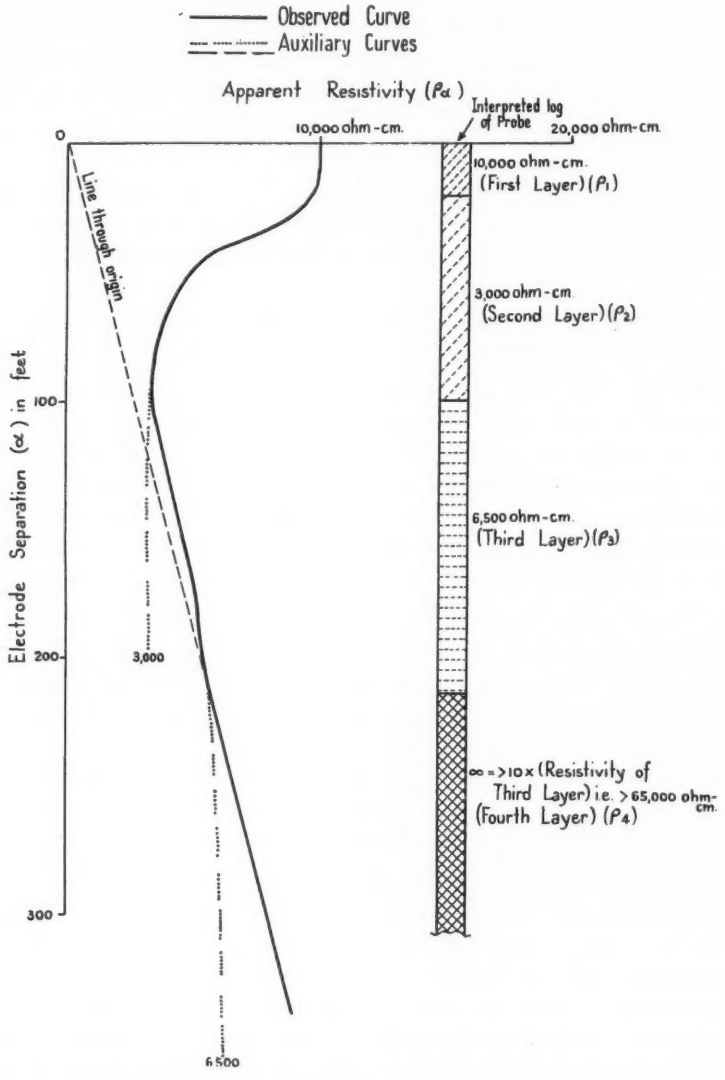


FIG. 14. Empirical interpretation of depth-probe curve.

In the second stage of the interpretation, the computed resistivities for each depth-probe curve are plotted as resistivity logs on a section showing the positions of the depth probes (such as in Fig. 15), and these are corrected for lateral effects. If the resistivities interpreted at adjacent depth-probe positions are identical, no lateral effects exist. If, on the other hand, the computed resistivities for the two

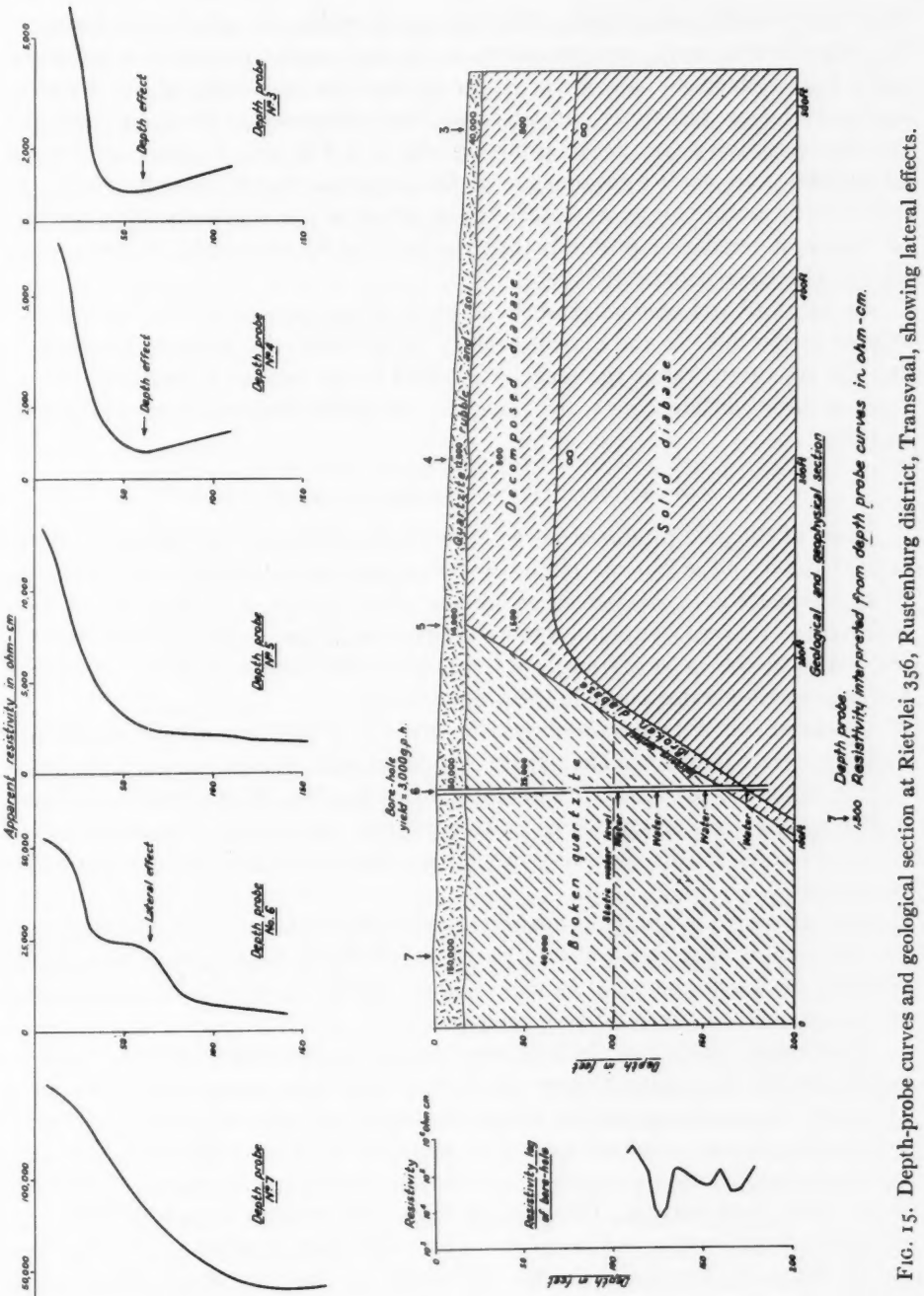


FIG. 15. Depth-probe curves and geological section at Rietvlei 356, Rustenburg district, Transvaal, showing lateral effects.

depth probes differ appreciably, then the one is within the sphere of influence of the other (Enslin, 1948), and the curve for the high resistivity position has necessarily been influenced to a great degree by the low resistivity of the adjacent position. The low resistivity curve has not been influenced to the same degree by the high resistivity (see depth probes 5 and 6 of Fig. 15). Corrections for the lateral effects are made by starting from the low-resistivity probes, estimating the effects on adjacent curves, and altering the values in the resistivity section where necessary. A resistivity profile is then constructed by connecting corresponding contacts between resistivity layers.

In the third and final stage of the interpretation, each resistivity layer is considered in the light of the known geology of the area, the mode of weathering, and the resistivity range that can be ascribed to the various formations. On the basis of these considerations, the resistivity profile is converted into a geological section.

GEOPHYSICAL PROSPECTING FOR GOLD

Most of the gold produced in the Union is mined from conglomerates, locally called banket, in the Witwatersrand system, a pre-Cambrian formation consisting of approximately 24,000 feet of sediments. This system is divided into a more argillaceous Lower Group and a more arenaceous Upper Group of beds. Some of the shales in the Lower Group are ferruginous and, hence, magnetic; the gold-bearing conglomerates occur in the Upper Group.

Rocks of the Witwatersrand system outcrop in the Central Witwatersrand, and also near Klerksdorp, Heidelberg, Vredefort, and in some other minor localities. In the Far West Rand, the East Rand, the Far East Rand, and in the Odendaalsrus area of the Orange Free State, however, the system is covered by more recent rocks to depths that may range from less than 1,000 feet to more than 10,000 feet.

The existence of the gold-bearing conglomerate under cover can be proved only by drilling. The choice of target areas for drilling is facilitated by geophysical methods because in some cases they make it possible to determine the presence of the upper Witwatersrand beds under cover.

Krahmann (1936) was the first geophysicist to take magnetometric traverses across the Witwatersrand System where it is covered by more recent formations. His object was to determine the positions, depths, and dips of the suboutcrops of known ferruginous shale beds from their magnetic anomalies. He would thus have been able to calculate the positions and the depths of the suboutcrops of the auriferous Main Reef horizon. The investigations were started in 1930 and by 1935 the Main Reef horizon had been traced for more than 30 miles on the Far West Rand. Magnetic surveys were also carried out on the East Rand (Weiss, 1936) and Far East Rand (Fox, 1939) and prospecting was then extended farther from the known outcrops into the Orange Free State. Here the exploration problem is to find Upper Witwatersrand beds containing the gold-bearing reefs at relatively shallow depths that will permit mining.

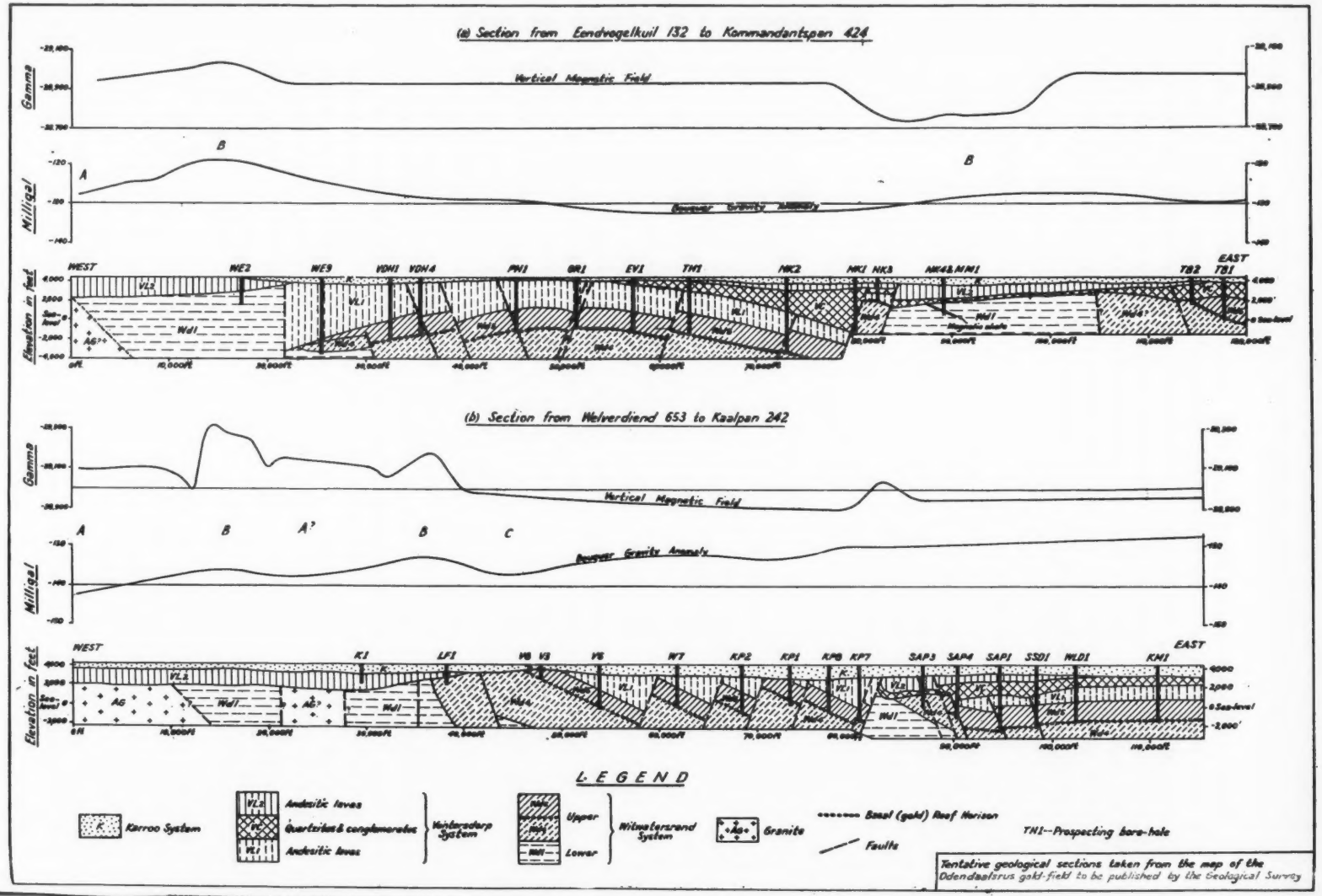
Weiss (1935) first suggested that the large changes in thickness of the andesitic lava of the Ventersdorp system overlying the arenaceous Witwatersrand system could probably be determined by the gravitational method because of the density contrast between these two systems. Average specific gravities of the Witwatersrand system and the other formations which form the floor or cover are given in Table I. These values have been determined by various investigators (Maree, 1944; Borchers and White, 1943; Frost et al., 1946).

TABLE I

Geological Formation	Specific Gravity
Karroo system	
sandstone and shale	2.3 –2.5
Transvaal system	
Pretoria Series (shale, quartzite, lava)	2.8
Dolomite	2.85
Ventersdorp system	
Andesitic lava	2.81–2.90
Acid lava and quartzite	2.68–2.76
Witwatersrand system	
Upper arenaceous beds	2.65–2.70
Lower argillaceous beds	2.80–2.90
Older Granite	2.65

On a traverse across the various surface exposures near Vredefort, the lowest gravity values are observed on the Older Granite, the first positive anomaly on the Lower Witwatersrand, low values again on the Upper Witwatersrand, and a second positive anomaly on the Ventersdorp and Transvaal systems.

In the Odendaalsrus gold field, Karroo shales and mudstones, with thickness up to 2,500 feet, rest on a slightly undulating surface of older rocks which are intensely broken up by pre-Karroo faults. The Witwatersrand system here is unconformably overlapped by the Ventersdorp system. The interpretation of the gravity and magnetic anomalies becomes extremely difficult in this area and in many cases no clear-cut interpretation can be made. The earlier gravitational surveys (Borchers and White, 1943; Frost et al., 1946) were carried out by torsion balance. The terrain, being flat, is ideal for surveys with this instrument. In some areas large local gradients and curvatures of gravity were caused by the irregular weathering of dolerite sills at the surface. These irregularities in some cases rendered the interpretations doubtful or valueless. A similar difficulty was encountered in the magnetic surveys because of the large polarization anomalies caused by the shallow dolerite sills, which in many cases completely masked the smaller deep-seated anomalies of the Lower Witwatersrand beds. Introduction of the gravimeter (Enslin, 1944) has eliminated the disturbing gravity effects of the dolerites near the surface while the difficulties due to near-surface polarization can be overcome by using the airborne magnetometer (Weiss, 1949).



...gional anomalies along section lines, Odendaalsrus gold field, Orange Free State.

Some of the pioneering surveys in the Odendaalsrus goldfield are described by Borchers and White (1943) and by Frost et al. (1946).

Two geological-geophysical sections across the Odendaalsrus gold field, compiled from unpublished surveys carried out by members of the staff of the Geological Survey, are shown in Figure 16. The section lines have approximate east-west bearings across the strike of the Witwatersrand beds, and are separated by distances of 14 and 8 miles, respectively, at their western and eastern extremities. The Bouguer gravity anomalies are based on a gravimeter survey; the vertical magnetic intensity curves obtained by surface observations have been smoothed to remove irregular anomalies caused by near-surface polarization of dolerite; and the geological sections are deduced from bore-hole data.

The salient features of Figure 16 illustrating the application of geophysical techniques to this and similar areas are as follows: At *A*, older granite is indicated by the large negative gravity anomaly and normal magnetic field intensity; at *B*, the positive gravity anomaly, accompanied by either positive or negative magnetic anomalies, is characteristic of the Lower Witwatersrand beds; at *C*, immediately adjoining anomaly *B*, a negative gravity anomaly and normal magnetic field indicate the economically important Upper Witwatersrand. The interpretation of the geophysical anomalies is more difficult in areas where faulting causes duplication of formations.

On the basis of the indications provided by the low-gravity zone *C* (section b, Fig. 16) which was originally located by a torsion balance survey (Frost et al., 1946) the first bore-hole in the St. Helena mine area was drilled in 1937–38. In this bore-hole, the Upper Witwatersrand was encountered at a depth of 991 feet, and payable gold was found in the underlying reef at a depth of less than 2,000 feet from the surface.

Other positive gravity anomalies that are unaccompanied by magnetic anomalies are assumed to indicate a thick cover of andesitic lavas of the Ventersdorp system. The gravity effect of the change in thickness of the Karroo sediments is superimposed on the pre-Karroo anomalies, and can be corrected for only if the thickness of the sediments is known.

A close study of the geophysical anomalies shows that the interpretation is not always straightforward. The interpretation of isolated geophysical surveys, which cover only small option areas, presents greater difficulties than the interpretation of regional surveys, which cover proved areas as well, and thus provide greater geological control.

The Geophysical Branch of the Geological Survey is carrying out systematic gravity and magnetic surveys of the Union as a whole, and in particular of potential areas in which the Witwatersrand system may occur under cover. The results of these surveys should ultimately give a much clearer picture of the possible distribution of other, currently unknown, units of the Witwatersrand system under cover of more recent rocks.

GEOPHYSICAL SURVEYS FOR OTHER MINERALS

Self-potential surveys have been made for nickel and copper ores, but with disappointing results. The limitation of this method in the Union results from the fact that the ores generally occur in rocks that are weathered only to depths much shallower than the zone of oxidation of the ore. The resistivity of the unweathered rock is too high to allow any measurable amounts of the self-potential current to reach the surface.

In the Barberton Goldfields, however, self-potential anomalies exceeding −1,000 millivolts were observed. These are caused by oxidation of sulphide ore which is associated with the gold in some of the reefs.

Extensive electromagnetic surveys have been carried out in the Rooiberg-Leeupoort Tinfields in the Transvaal. It was possible to trace not only most of the known tin-bearing lodes and fault zones but also a number of unknown faults, some of which were afterwards proved to be economically mineralized. Similar surveys were made on some of the fault zones associated with the copper mineralization in the Messina area of the Northern Transvaal, and it was found that most of them could be traced easily by the H_T-method.

Radioactivity logging has been undertaken in about 100 deep narrow-diameter bore-holes drilled in prospecting for gold, with specially designed equipment for the location of uraniferous conglomerates in the Witwatersrand system. The results (Simpson and Bouwer, 1950; Simpson, 1951; Simpson, 1952) indicate that the uranium was deposited in a cyclic manner and it was possible to correlate the various uraniferous horizons in widely separated areas.

GEOPHYSICAL SURVEYS FOR ENGINEERING STUDIES

Resistivity surveys of possible sites for bridges and dams have yielded valuable results, especially where the bedrock is igneous, in which case it has been possible to prepare contour maps showing the depths of alluvium or weathered rock.

Gough (1952) designed a new type of seismic instrument for shallow refraction surveys. A sledge-hammer is used as the source of seismic energy, and contacts down to depths of 100 feet can be determined. This instrument is useful in areas where results cannot be obtained by resistivity surveys either because of excessive lateral effects or because of the absence of a resistivity contrast at the bedrock surface.

The collapse of the surface as sinkholes in dolomite areas (Enslin, 1951) has caused damage to buildings, reservoirs and main roads, especially south of Pretoria. Extensive magnetic, resistivity, electromagnetic, and gravitational surveys have been carried out for delineating the danger zones for sinkholes. Large inliers of Karroo sediments in the dolomite, which are considered safe from sinkhole-type erosion have been located by their basin-shaped negative gravity anomalies. The runways of the Waterkloof air station have been built on one of these inliers. Sinkholes are often aligned along major fault planes in the dolomite.

Because of the homogeneous nature of the dolomite it is very difficult to trace such fault planes from surface geological indications. Some success has been achieved in locating and following a number of such fault planes by the H_T-electromagnetic method.

ACKNOWLEDGMENTS

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GEOPHYSICS, VOL. XX, NO. 4 (OCTOBER, 1955), PP. 913–931, 10 FIGS.

THE APPLICATION OF A THREE-ELEMENT MODEL TO THE S.P. AND RESISTIVITY PHENOMENA EVINCED BY DIRTY SANDS*

J. G. McKELVEY, JR.,† P. F. SOUTHWICK,† K. S. SPIEGLER,† AND M. R. J. WYLLIE†

ABSTRACT

A simple resistor model consisting of three elements in parallel and representing (a) an element of solution and conducting solid particles in series, (b) an element of the solid particles only, and (c) an element of solution only, explains satisfactorily the experimental relationship between the conductivities of solutions used to saturate synthetic dirty sands and the conductivities of the saturated sands. The synthetic dirty sands consist of beds of ion-exchange particles.

The same model is applied to give a theoretical explanation of the potential differences between two different solutions when these meet in the interstices of a synthetic dirty sand; excellent agreement is observed between theory and experiment. It is found that both potentials and resistivities depend on the same geometrical parameters. Hence they can be related to each other. The relationship is derived between the self-potential deflection and the resistivities of rock and invaded zone. It is compared to various formulae proposed by other investigators for interpreting logs in dirty sands.

Conductivities and potential differences across plugs of "synthetic dirty sands" containing oil have been measured. At high oil saturations the potential differences are almost as high as those across a solid membrane containing the same ion-exchange resin.

INTRODUCTION

In a previous investigation (Wyllie and Southwick, 1954) laboratory experiments were reported on the electrical conductivity of dirty sands (i.e., sands containing conductive clays) and on the electrical potentials across them. In these experiments natural and "synthetic" dirty sands were used. The latter are mixtures of synthetic ion-exchange resins and glass spheres or even aggregates consisting only of ion-exchange resins. While such mixtures do not occur in nature, they were used as models of the natural sands containing dispersed clays. Because of their base-exchange properties, synthetic cation-exchange resins are electrochemically equivalent to natural clays. However, in the "synthetic dirty sands" these properties are magnified. Because of their higher exchange capacity and the higher mobility of their ions (Schulze, 1914; Spiegler, 1953), the resins enhance the effects of the base-exchange and ion-permeability properties of natural clays. The resins are therefore well suited for fundamental electrochemical studies of shales and dirty sands. In applying the results of these studies to natural formations, the mechanical dissimilarity of the synthetic and natural dirty sands must be kept in mind as much as their electrochemical similarity.

It was found that the electrical conductance of plugs composed of ion-exchange resins saturated with solutions can be represented by a simple model. This model consists of three resistor elements in parallel, representing (a) an

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element made up of solution and particle conductances in series, (b) an element of particles only, and (c) an element of solution only. By analyzing the variation of the total resistivity (specific resistance) of the plug with the resistivity of the solution saturating it, one can calculate the relative contribution of each of these three elements (Wyllie and Southwick, 1954; Sauer et al., in press). It is believed that this model is generally valid for porous plugs containing solid ionic conductors. In the present paper is it shown how this same model can be applied to the quantitative interpretation of *potentials* across conductive porous plugs separating solutions of different concentration. The influence of oil or other non-conducting liquids is discussed and some experiments demonstrating this influence are reported.

THEORY

Plug Potential Expressed in Conductance Parameters

Figure 1 represents the model of a conducting porous plug, as described previously (Wyllie and Southwick, 1954; Sauer et al., in press), inserted between

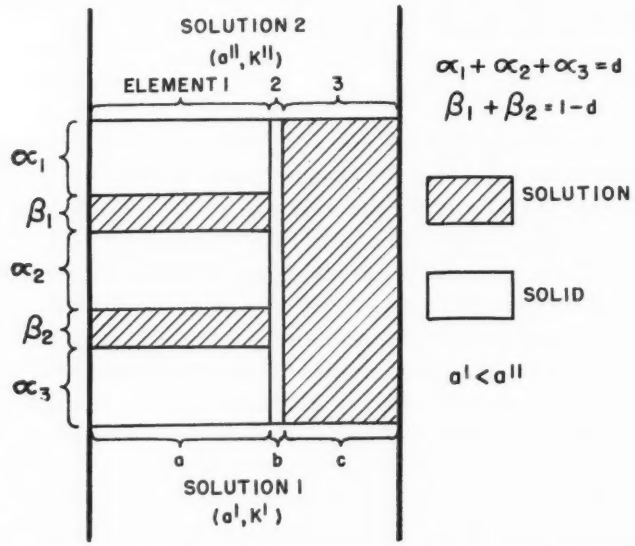


FIG. 1. Simplified model representing conducting porous plug separating two solutions.

two solutions of sodium chloride of different concentrations. Element 1 consists of alternating layers of solid and solution, element 2 of solid only, and element 3 of solution. If each of these three elements were existing separately, they would cause the following potentials between the two solutions.

Element 1.—The potential across an element separated by alternating layers of membranes and dilute solutions is equal to the membrane potential between the terminal solutions (as proved in the Appendix). In other words, it makes no

difference how many membranes there are or what kind of concentration distribution exists in the solutions between them, as long as the membranes are ideally cation permeable. The whole of element 1 acts like an ideal membrane and in dilute solutions the potential difference, E_M, (in millivolts) across this membrane is therefore given by

$$E_M = 59.2 \log \frac{a'}{a''} \text{ (at 25°C, for ideal membranes)} \qquad (1)$$

where a' and a'' are the mean activities of sodium chloride in the terminal solutions. Derivations of equation (1) have been presented by many authors, such as Spiegler and Wyllie (in press). A membrane is said to be electrochemically "ideal" if its potential approaches that calculated from equation (1).

Element 2.—This element consists only of solid. It represents a single cation-permeable membrane and in dilute solutions, therefore, the potential E_M across it is given by equation (1) also.

Element 3.—Since this element consists only of solution, the potential across it is the junction potential between the two solutions (often also called the "diffusion potential"). This potential, E_J, is given by (Spiegler and Wyllie, in press)

$$E_J = 59.2(2t^+ - 1) \log \frac{a'}{a''} \cong -12 \log \frac{a'}{a''} \text{ (at 25°C).} \qquad (2)$$

where t^+ is the average transference number of the sodium ions.

Since for sodium chloride $t^+ \cong 0.4$, the potential difference across element 3 has a sign opposite to that across elements 1 and 2.

These are the potentials which would arise if only one of the respective elements were present to the exclusion of the others. The actual "plug potential" between solutions 1 and 2 is a composite of the membrane potential caused by elements 1 and 2 and the junction potential caused by element 3. One may consider the plug as a "leaky" membrane with (a) elements 1 and 2 as the intact portion causing a potential with solution 1 electrically positive with respect to solution 2, and (b) element 3 as the "leak." If the solute is sodium chloride, the junction potential of element 3 counteracts the membrane potential and tends to make solution 1 negative with respect to solution 2.

This circuit is schematically represented in Figure 2. By Kirchhoff's laws the total observed potential E can be expressed as follows:

$$E = E_M \frac{K_1 + K_2}{K_1 + K_2 + K_3} + E_J \frac{K_3}{K_1 + K_2 + K_3}$$
$$= f_M E_M + f_J E_J = f_M E_M + (1 - f_M) E_J \qquad (3)$$

where K_1, K_2, and K_3 are the respective contributions of the three elements to the total conductivity of the plug (mho-cm^{-1}). f_M and f_J are the fractions of the

plug conductance due to the membrane (1 and 2) and solution elements respectively.[1]

It is seen that the contribution of the membrane and junction potentials to the total potential depends, in a simple fashion, on the conductances of the elements of the resistor. When the solution concentrations are high, the conductance of element 3 is relatively high and the magnitude of the plug potential is close to that of the junction potential between the two salt solutions. The porous plug then acts as a clean sand. On the other hand, when the conductivity of the solutions is low, the ion current flows mainly through elements 1 and 2 and the porous plug acts in this case as an ideal membrane.

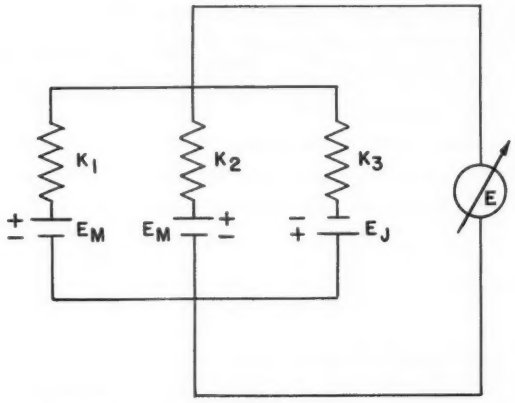


FIG. 2. Potentials and resistors representing an ion-conductive porous plug separating two salt solutions.

The factors f_M and f_J may be calculated from the geometrical parameters a, b, c, and d of the plug (Figure 1), the conductivity (specific conductance) of the solid, K_R, and the average conductivity of the solutions, $\overline{K}_w$. The expressions follow directly from Ohm's law and they have been derived and discussed by Wyllie and Southwick (1954) and by Sauer et al. (in press).[2] The resulting expressions are as follows:

[1] Equation (3) can also be derived by a standard thermodynamic reasoning. In a hypothetical experiment two reversible electrodes are inserted in the two solutions. One Faraday is allowed to pass from one solution to the other under reversible conditions. It is asked what fraction of the current passes through each of the elements of the model (Fig. 1) and what results are produced by the passage of the current. The total decrease of the free energy of the system is then set equal to the electrical work.

[2] The parameters x, y, z, and F used by Wyllie and Southwick are related to a, b, c, and d in the following manner:

$$x \equiv \frac{1-d}{a}, \quad y \equiv \frac{d}{a}, \quad z \equiv \frac{1}{b}, \quad F = \frac{1}{c}.$$

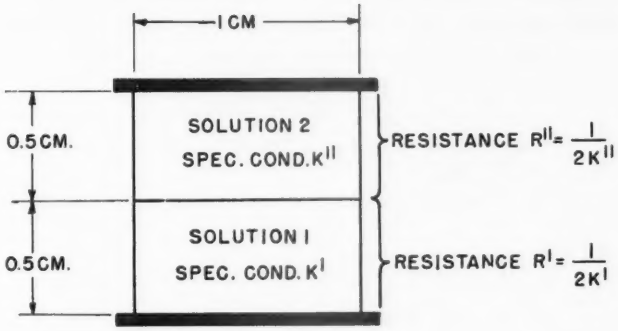
$$K_1 = \frac{aK_R\overline{K}_w}{(1-d)K_R + d\overline{K}_w} \tag{4}$$

$$K_2 = bK_R \tag{5}$$

$$K_3 = c\overline{K}_w = \frac{\overline{K}_w}{F} \tag{6}$$

where F is the true formation factor which would prevail if all conductive particles were replaced by identical non-conducting ones.

The formulae as originally derived refer to plugs saturated entirely with one solution of specific conductance K_w. If the plug separates two solutions of different concentrations, a suitable average conductivity, $\overline{K}_w$, is substituted in the equa-



$$\text{TOTAL RESISTANCE} = R^I + R^{II} = \frac{1}{2K^I} + \frac{1}{2K^{II}}$$

$$\text{TOTAL CONDUCTANCE} = \frac{2K^IK^{II}}{K^I + K^{II}}$$

FIG. 3. Calculation of "average specific conductance" of the solutions saturating the plug.

tions. The type of average depends on the concentration distribution across the plug. As an approximation it is here assumed that the upper half of the plug is saturated entirely with one solution and the lower half with the other, as shown in Figure 3. The average conductivity, $\overline{K}_w$, is

$$\overline{K}_w = \frac{2K'K''}{K' + K''} \tag{7}$$

where K' and K'' are the conductivities of the respective solutions.

It is important that a, b, c, and d and K_R can be determined from the variation of the specific conductance, K_0, of the plug as the specific conductance, K_w, of the solution varies. Wyllie and Southwick (1954) deal with this question in detail, as do Sauer et al. (in press). Once these parameters are known, f_M can be calcu-

lated from the formula

$$f_M = \frac{K_1 + K_2}{K_0} =$$

$$\left[\frac{aK_R\overline{K}_w}{(1-d)K_R + d\overline{K}_w} + bK_R\right] \Big/ \left[\frac{aK_R\overline{K}_w}{(1-d)K_R + d\overline{K}_w} + bK_R - c\overline{K}_w\right] \quad (8)$$

and substituted in equation (3) for the calculation of the plug potential E. In

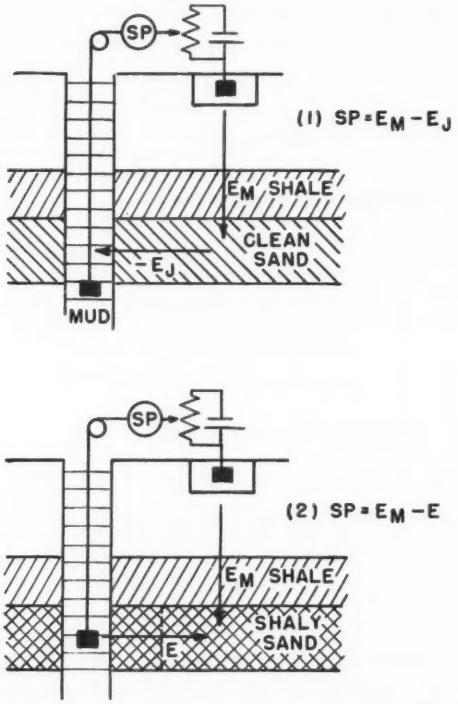


FIG. 4. Schematic diagram of potentials: (1) in a clean sand, (2) in a shaly sand. Arrows point from positive to negative.

other words, it is thus possible to calculate the *potential* across an ion-conducting plug from *conductance* data. It is shown in the experimental section that laboratory measurements of potentials across plugs of ion-exchange resins are indeed in agreement with those calculated by combining equations (3) and (8) when the conductance data of the same resins are used.

Equation (1) holds strictly only when the solution concentrations are low and the resin particles, therefore, act as ideal membranes. Otherwise, the E_M values to be used in equation (3) are lower than those calculated from equation (1). For certain ion-exchange resin materials, the correction based on the departure from

electrochemically ideal behavior has been reported by Winger et al. (1953). It is believed that in time the corresponding corrections for conductive clays will also be measured. Some information on this subject is already available from work by Marshall (1949) on potentials across clay membranes. Marshall found that clay membranes, like ion-exchange resins, may be considered as relatively "ideal" from an electrochemical standpoint.

The relation between the plug potential, E, described here and the self-potential deflection, $S.P.$, measured in well logging is shown schematically in Figure 4.

Oil-Bearing Sands

If oil is present, both plug potential and conductance depend on the oil saturation. The presence of oil enhances the relative importance of elements 1 and 2 of

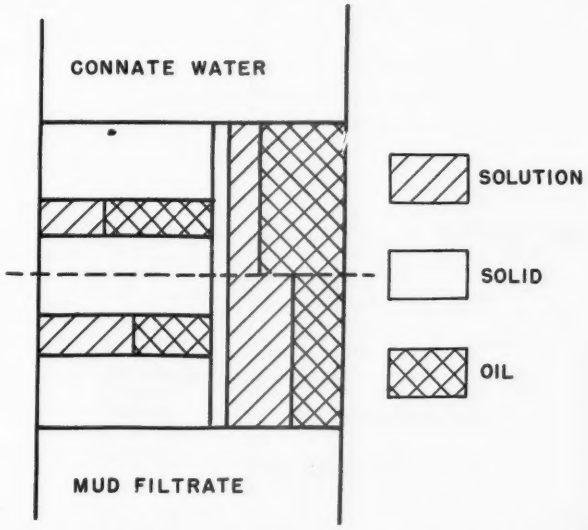


FIG. 5. Simplified model representing oil-bearing shaly sand.

the resistor model because the conductance of the solution element 3 is greatly reduced. Hence with increasing oil saturation the potential difference across the dirty sand becomes more similar to that across a shale and the $S.P.$ deflection decreases. This situation is illustrated in Figure 5.

The quantitative theory of potentials across oil-containing plugs, as represented in Figure 5, has been developed but is not reported here. In these computations the K_w terms are replaced by terms K_w/I. I is a resisitivity index which is, in general, different in the solution sections in element 1 and in element 3. At high oil saturations one expects almost complete loss of conductivity in element 3. The current is then carried almost entirely by elements 1 and 2. It

was indeed found that the potential difference across the ion-exchange resin plug approaches the potential difference across a dense membrane of the same material if the oil saturation is high. The oil reduces the electrochemical "leaks" in the porous plug. Experimental work is still in progress on the influence of the oil saturation upon potentials and conductivities in conducting plugs.

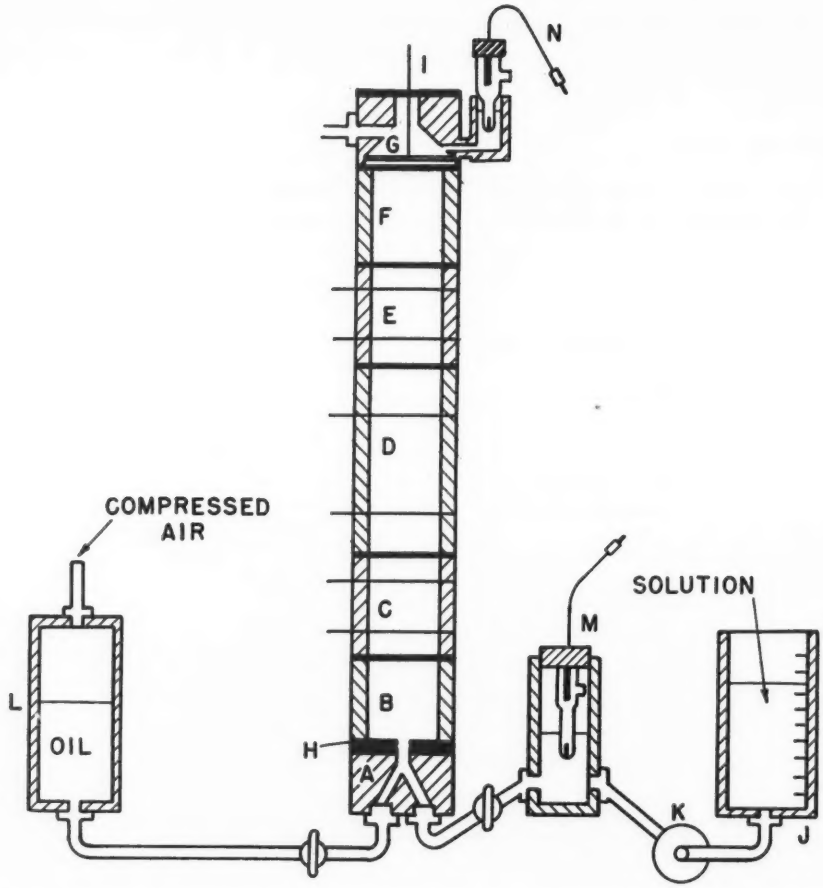


FIG. 6. Schematic diagram of apparatus for conductance and potential measurements of porous plugs. A–G. Lucite column sections; H, I. Platinum electrodes; J. Solution reservoir; K. Pump; L. Oil reservoir; M, N. Calomel electrodes.

EXPERIMENTAL

In these experiments a column was filled with a cation-exchange resin saturated with a solution and, in some cases, with oil also. A solution of different concentration was then passed into the column in the upward direction. As long as the front between the two solutions was in the resin column, a potential difference could be measured between calomel electrodes in the two solutions.

Determination of these potential differences and the conductance of the column at various stages of the operation was the object of this study.

The apparatus for the measurement of conductances and potentials in porous plugs saturated only with *aqueous* solutions has already been described (Wyllie and Southwick, 1954).

The apparatus used for the experiments with "synthetic *oil-bearing* dirty sands" is a modification of the previous equipment. It is shown schematically in Figure 6. It consists of seven "Lucite" sections A–G, of outer diameter 2 inches and inner diameter $1\frac{1}{4}$ inches. These sections are equipped with threads and screwed

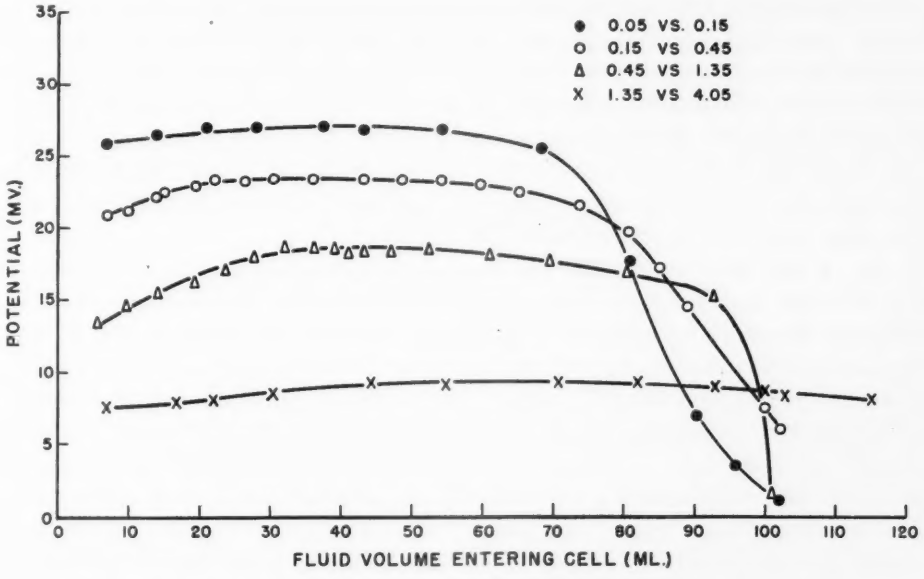


FIG. 7. Potentials between two sodium chloride solutions separated by a "synthetic oil-saturated shaly sand." Activity ratio, 1:3.

together, thus forming a continuous column. Sections B–F were filled with the cation-exchange resin "Amberlite IR-120,"[3] an electrochemical analogue of a very dirty sand. The total length of the resin column was 55 cm. The resin was held between a perforated platinum electrode *H* at the bottom and a platinum mesh electrode *I* at the top. Each of the sections C, D, and E contains one pair of probe electrodes consisting of platinum wires (1 mm diameter) strung across the column.

The experiments involved the following operations.

(a). The resin was first saturated with a sodium chloride solution. This solution was pumped through the column from a reservoir *J* by means of a "Zenith"

[3] Product of the Rohm & Haas Company, Philadelphia, Pennsylvania.

metering gear pump, *K*. In this operation care was taken to avoid the introduction of air bubbles into the column. The conductance of the resin sections C, D, and E was then measured by passing a current of 0.01 amp (60 cps) through the terminal electrodes *H* and *I* and measuring the potential difference across the probe electrodes in each of the sections. The cell constants of these sections had been determined by calibration with 0.01-, 0.1-, and 1-*N* potassium chloride solutions. The maximum differences between these calibrations were less than one percent.

(b). After these conductance measurements, oil was introduced into the column from the reservoir *L*. The oil used was "Gulf Mechanism Oil A." Sufficient bromoform had been added to it to adjust the density to a value between that of the sodium chloride solution used previously and the more concentrated solution used in the next step. The oil was compressed into the column by air under a pressure of about 6 inches of mercury. The oil replaced the major portion of the interstitial solution in the column, leaving only a few percent of residual solution adhering to the resin particles. The conductance of the sections decreased. The passage of oil was continued until the conductance reached a constant level. The plug was now considered to be "oil-saturated."

(c). A new sodium chloride solution, with activity threefold the previous one, was now passed through the column from reservoir *J* through pump *K*. The potential difference between two "Beckman" calomel electrodes *M* and *N* was measured during the passage of this solution. The measuring instrument was a Leeds and Northrup potentiometer with a sensitive galvanometer. The accuracy of the potential measurements was 0.1 mv. As the solution front moved through the column, the potential difference reached a constant value and then dropped abruptly. This is shown in Figure 7. During the potential measurement proper the flow of solution was stopped. The plateau value was taken as the plug potential. Correction was made for the assymetry of the salt bridge potentials of the calomel electrodes.[4] The conductance of sections C, D, and E was again measured immediately after the drop of the potential occurred.

(d). The column was now flushed with the salt solution until the conductance in each of the sections reached a constant value.

The column was again saturated with oil, as described under (b), and operations (c) and (d) were then repeated with a sodium chloride solution of threefold activity. Altogether five sodium chloride solutions were used: The most concentrated one was 4.77 molal (278.8 g NaCl per 1000 g water). The activity of this solution was 4.05.

[4] The salt bridge junction potential was calculated from Henderson's formula assuming that the mobilities of K^+ and Cl^- are equal (Spiegler and Wyllie, in press). It should be noted that Henderson's formula is strictly applicable only to very dilute solutions and the correction is therefore not very accurate. The correction increases with the solution concentration and the largest correction applied was 1.6 mv.

RESULTS

Plug Potentials in the Absence of Oil

Figure 8 represents the potentials measured between two aqueous sodium chloride solutions separated by a plug of "Amberlite IR-120." The particle size of the resin used in these experiments was between 14 and 16 mesh U. S. Standard Screen Series.[5] The ratio of the mean activities of the solutions was 1:2. These values have already been reported (Wyllie and Southwick, 1954) but are replotted here in terms of the plug potential, E versus the average activity, $\bar{a}$ of the solutions for the sake of comparison with the theory.

The circles represent the measured potentials (corrected for the estimated difference of the junction potentials of the calomel electrodes). The solid line is calculated from the theory (equations (3) and (8)). The various parameters in these equations were determined by mathematical analysis of the conductance data as described in detail by Wyllie and Southwick (1954). The values of the parameters for this plug are as follows:

$$K_R = 0.019 \text{ mho-cm}^{-1}$$
$$a = 0.67$$
$$b = 0.013$$
$$c = 0.317$$
$$d = 0.865.$$

The values of E_M, the potentials of a pure resin membrane between the various pairs of solutions, were measured for an "Amberplex C-1"[6] membrane. They are also shown in Figure 8.

It is seen that the ion-exchange membrane, as well as the porous plug of the ion-exchange resin, deviates from the "ideal potential." In the resin membrane, this is due primarily to the "Donnan effect," whereas in the plug, additional electrical "leaks" occur because of conduction through the interstitial solution. These "leaks" decrease the plug potential. The lower limit for this potential is the junction potential, E_J, which should be asymptotically approached at very high solution concentrations. In view of the many simplifying assumptions made in the development of the theory, the agreement between theory and experiments is considered satisfactory.

Plug Potentials in the Presence of Oil

Figure 9 shows the potential differences between two calomel electrodes in contact with the two sodium chloride solutions at the top and the bottom of the resin column. The potentials are plotted against the average activity of the solutions and corrected for the difference of the junction potentials of the calomel

[5] In Wyllie and Southwick (1954) the particle size is erronepusly listed as 40-50 mesh.

[6] Product of the Rohm & Haas Company, Philadelphia, Pennsylvania. This membrane contains an ion-exchange resin similar to "Amberlite IR-120" and inert plastic binder (Winger et al., 1953).

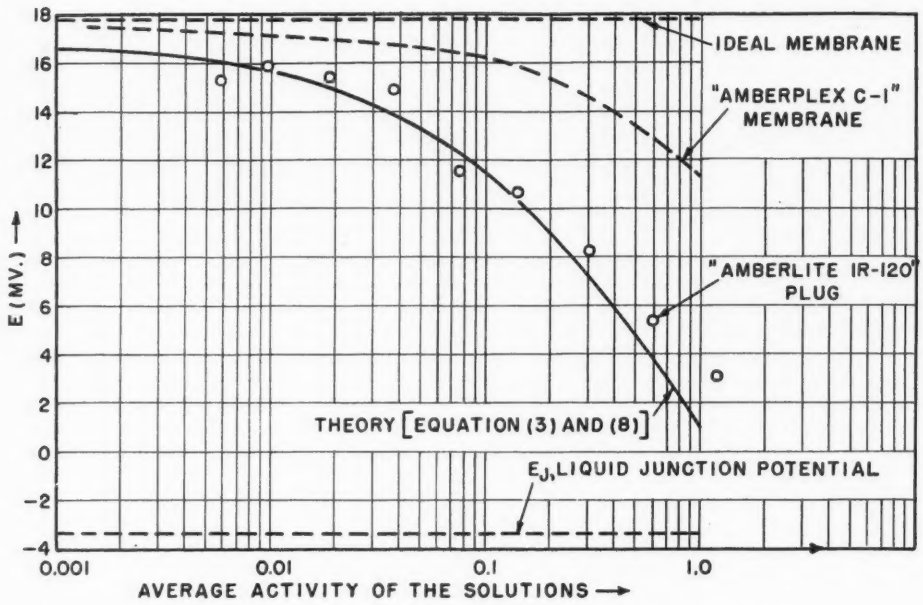


FIG. 8. Potentials across a plug of "Amberlite IR-120" resin. Solution is sodium chloride. Activity ratio is 1:2. Temperature is 25°C.

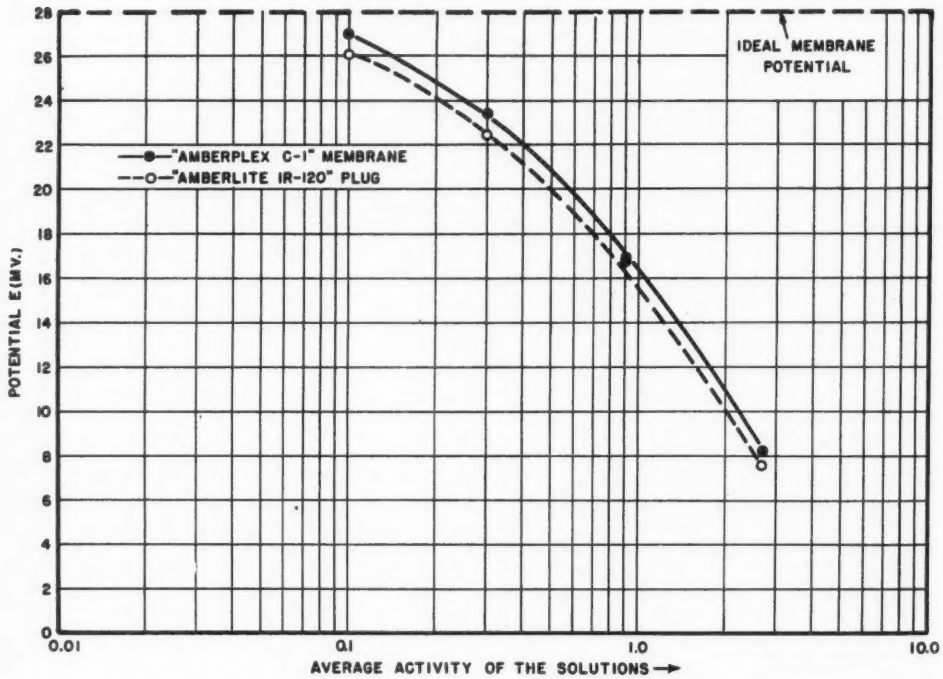


FIG. 9. Potentials across oil-saturated plug of "Amberlite IR-120" resin. Solution is sodium chloride. Activity ratio is 1:3. Temperature is 25°C.

electrodes. The resin was originally saturated with the more dilute solution and then oil-saturated. The resin used in these experiments was ground to a size of 40–50 mesh, U. S. Standard Screen (dry-sieved). The particle size was therefore much smaller than in the experiments reported at the beginning of this section.

For comparison, the potentials across "Amberplex C-1" are also shown in Figure 9. It is seen that the potentials measured across the oil-bearing ion-exchange resin plug are only slightly less than those measured across the solid-resin membrane "Amberplex C-1." The latter consists of finely powdered resin and an inert plastic binder and has no interstices for the solution. The oil in the interstices of the plug therefore acts electrochemically like the plastic in the membrane. The presence of the oil thus enhances the "dirtiness" of the bed.

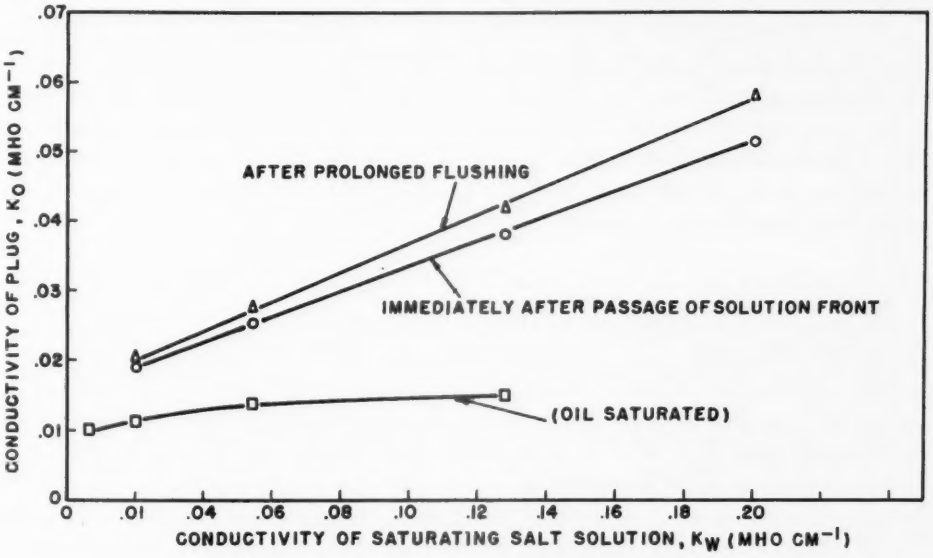


FIG. 10. Specific conductance of a plug of "Amberlite IR-120" resin containing solution of common salt and oil.

These experiments describe the extreme case of potentials across a very dirty "synthetic sand" at high oil saturation. Additional experiments are planned on potentials at lower oil saturation.

Figure 10 shows the conductivity of the porous plug under various conditions. The plug conductivity is plotted against the conductivity of the interstitial solution in the presence of oil. The values plotted here represent the average of the conductivities measured in sections C, D, and E. These values varied within limits of not more than two percent.

The lowest curve describes the conductivity of the plug when "oil-saturated." In this case, a film of solution still adheres to the resin particles. This film, together with the solid, provides a conductive path and thus accounts for the elec-

trical conductance of the plug. When another solution is forced into the column, displacement of the oil occurs. The front between the incoming concentrated solution, on the one hand, and the oil and dilute solution, on the other, is not a sharp one. The middle curve in Figure 9 represents the conductivities measured just after the potential between the calomel electrodes has dropped to zero (Figure 7). This was taken as an indication that the more dilute solution had been completely removed from the column. Additional flushing with the more concentrated solution removed more oil from the column and caused an increase of conductivity. Finally, a constant conductivity value was reached, although a certain amount of residual oil still remained in the column. The upper curve in Figure 9 represents the final constant conductivity values plotted for different concentrations of the displacement solution.

It is seen that the two upper curves are almost straight lines. Some curvature, concave with respect to the abscissa, is observed for the lower concentration in the lowest curve. When the curves are extrapolated towards low concentrations, a positive intercept on the ordinate is obtained. This shape of the conductance curves is characteristic of conductive plugs; for plugs containing no oil, the characteristics of the curves have been discussed in detail by Wyllie and Southwick (1954) and Sauer et al. (in press).

DISCUSSION

In our previous investigations the electrical conductance of porous plugs consisting of conductive solids and solutions was found to conform to a resistor model, as shown in Figure 1. In an earlier section of this paper, this theory was extended to potentials across such plugs. The potentials measured in the absence of oil were compared with those derived from theory and fair agreement was found (Figure 8). It is therefore believed that this model explains the electrical resistance of conductive plugs and the potential differences across them. Since the potential and conductance data are related to the same geometrical parameters, they are also related to each other. Their relation will be derived in this section.

It should be kept in mind that the laboratory experiments were carried out with relatively coarse ion-exchange resins rather than the porous dirty sands found in nature. However, since the model is based on purely geometrical considerations, the theory should also hold for natural dirty sands; the numerical values of the geometrical parameters a, b, c, and d are probably different for them. The numerous recent publications on log interpretation in natural dirty sands are not reviewed here. A bibliography may be found in an important recent paper on this subject by Poupon, Loy, and Tixier (1954).

From equations (4), (5), and (6) we obtain for the total plug conductivity,

$$K_0 = K_1 + K_2 + K_3 = \frac{aK_R\overline{K}_w}{(1-d)K_R + d\overline{K}_w} + bK_R + \frac{\overline{K}_w}{F}. \qquad (9)$$

This is equation (11) of the paper by Wyllie and Southwick (1954), with x, y, and z substituted in terms of the geometrical parameters a, b, and d, and the solution conductivity, K_w, replaced by the *average* solution conductivity, $\overline{K}_w$.

In natural shaly sands $(1-d)K_R$ is often much smaller than $d\overline{K}_w$. In other words, the resistivity of the solid component determines the total resistance of resistor element 1 in Figure 1. Thus equation (9) reduces to the approximate form

$$K_0 \cong \left(\frac{a}{d} + b\right) K_R + \frac{\overline{K}_w}{F} = A + \frac{\overline{K}_w}{F} \tag{10}$$

or

$$\frac{1}{R_0} \cong \left(\frac{a}{d} + b\right) \frac{1}{R_R} + \frac{\overline{K}_w}{F} = A + \frac{1}{F\overline{R}_w} \tag{11}$$

where R_0, R_R, and $\overline{R}_w$ are the resistivities (specific resistances) of the plug (shaly sand) and the solid (conducting clay) respectively. $\overline{R}_w$ is the average resistivity of two solutions in series (Figure 3). A is defined as

$$A = \left(\frac{a}{d} + b\right) K_R. \tag{12}$$

Inasmuch as R_R is independent of the solution concentration, equations (10) and (11) are in agreement with the earlier equation of Patnode and Wyllie (1950). The latter states that the conductivity of a shaly sand is equal to the conductivity of an equivalent clean sand (K_w/F) plus a constant term. This term is now identified as $[(a/d)+b]K_R$.

With the same simplifying assumptions which led to equation (10) we obtain an expression for f_M from equation (8):

$$f_M = \frac{K_1 + K_2}{K_0} \cong \frac{A}{A + (\overline{K}_w/F)} \quad \overline{K}_w \gg K_R. \tag{13}$$

This expression is now used for the calculation of the self potential deflection *S.P.* The latter is equal to the membrane potential (characteristic of the shale baseline) minus the potential, E, developed in the sand:[7]

$$S.P. = E_M - E. \tag{14}$$

In this equation, E_M represents the ideal membrane potential since shale layers seem to act like ideal membranes. Substituting f_M from equation (13) in equation (3) and combining with equation (14), we obtain

[7] The junction potential E developed in a clean sand between mud filtrate and connate water of higher concentration is to be taken negative. The potential, E, in a very dirty sand is positive; the higher the shale percentage in the sand the closer is the value of E to E_M and the lower is the self-potential deflection, *S.P.* (Fig. 4).

$$S.P. = (E_M - E_J)\frac{(\overline{K}_w/F)}{A + (\overline{K}_w/F)}. \tag{15}$$

It is common practice to substitute the conductivity ratio for the activity ratio in equations (1) and (2). In this case we obtain:

$$S.P. = 71\frac{\overline{K}_w}{AF + \overline{K}_w}\log\frac{R_{mf}}{R_w}\ (\text{at } 25°\text{C.}) \tag{16}$$

where R_{mf} and R_w are the resistivities of mud filtrate and connate water respectively.

R_{mf} and R_w are now expressed in terms of the resistivities R_{X0} and R_0 of the invaded zone and of the formation, respectively, since these latter may be read from the resistivity logs. We apply equation (11) to the invaded zone and the formation:

$$\frac{1}{R_{X0}} = A + \frac{1}{FR_{mf}} \tag{17}$$

$$\frac{1}{R_0} = A + \frac{1}{FR_w}. \tag{18}$$

Substituting the values of R_{mf} and R_w from equations (17) and (18) in equation (16), we obtain for the S.P. in a dirty sand:

$$S.P. = 71\frac{1}{AF\overline{R}_w + 1}\log\frac{R_{X0}(1 - AR_0)}{R_0(1 - AR_{X0})}\ (\text{at } 25°\text{C.}). \tag{19}$$

In this case $\overline{R}_w$ is the appropriate average of the resistivities of mud filtrate and connate water.[8]

It is customary to plot R_{X0}/R_0 as a function of $S.P.$ on semilog paper (Poupon, Loy, and Tixier, 1954). If the formation studied is a clean sand, a straight line is obtained, since for *clean* sands the following relationship holds (Wyllie, 1954):

$$S.P. = 71\log\frac{R_{X0}}{R_0}\ (\text{at } 25°\text{C.}). \tag{20}$$

[8] In the derivation of the fundamental equations, it has been assumed that a sharp boundary exists between the two solutions (Fig. 3) and that the resistivity $\overline{R}_w$ is the *arithmetic* mean of the resistivities of the two solutions. In reality, the situation is considerably more complex. If the concentrations of the two solutions are not very different, the arithmetic mean represents a good approximation. This is proved by the results shown in Figure 8. The activity ratio of the two solutions on the two sides of the membrane was 2 in these experiments. For large concentration ratios another type of average such as the *logarithmic* average may yield better agreement with the theory. This question is still under investigation and it is to be understood that the range of applicability of equation (19) is limited to relatively small concentration differences if $\overline{R}_w$ is taken as the arithmetic mean of the resistivities of the solutions.

Comparison of equations (19) and (20) shows how the presence of shale in the sand modifies the relationship between the S.P. and the resistivities. For a dirty water sand the factor before the logarithmic term is *smaller* than for a clean water sand. On the other hand, the logarithmic term is *larger* for the dirty than for the clean sand. It is possible that these two factors will often approximately counterbalance each other. This would explain the finding (equation (1) of Poupon, Loy, and Tixier, 1954) that equation (20) applies approximately to shaly as well as to clean sands.

It is also of interest to compare the conductance equation (11) with an equation of de Witte (1950) for dirty sands:

$$\frac{1}{R_0} = \frac{q}{R_R} + \frac{1-q}{R_w} \tag{21}$$

where q is the proportion of the porosity occupied by the conductive solids. If the numerical values of a, c, and d are substituted in equation (11) we obtain:

$$\frac{1}{R_0} = \frac{0.78}{R_R} + \frac{0.32}{R_w} \tag{22}$$

for the plug described by Wyllie and Southwick, 1954, and

$$\frac{1}{R_0} = \frac{0.66}{R_R} + \frac{0.35}{R_w} \tag{23}$$

for the plug described by Sauer et al. (in press).

The resins in the two plugs were of different particle size.

Since the volume fraction of the resin was roughly 60 to 65 percent, it is seen that the de Witte formula yields approximately the correct conductance (within the range of applicability of equation (11); i.e., when $K_w \gg K_R$). This is of interest since the formula was based on the analogy between a homogeneous mixture of conductive solids and a salt solution, on the one hand, and a mixture of two salt solutions, on the other. The particle size of the resins was rather coarse; hence the plugs examined were quite different from a homogeneous mixture of two solutions. Yet it is seen that the formula approximates the results reasonably well.

It should be noted that the three-resistor model which served as a basis for the preceding considerations represents sands with *dispersed* conductive clays, rather than laminated beds consisting of alternating thin layers of shale and sand.

SUMMARY OF NOMENCLATURE

A	A constant defined in equation (12)
a	Activity (mole per liter)
a, b, c, d	Geometrical factors as shown in Figure 1
E	Plug potential (the potential difference measured between two calomel electrodes in the two solution at opposite ends of a porous plug) (mv)

E_J	Junction potential (mv)
E_M	Membrane potential of a cation-selective membrane (mv)
F	True formation factor
f_J	Fraction of the plug conductance due to element 3 (Figure 1)
f_M	Fraction of the plug conductance due to elements 1 and 2 (Figure 1)
I	Resistivity index
K_0	Conductivity of the porous plug (mho-cm^{-1})
K_1, K_2, K_3	Contributions of the elements 1, 2 and 3 of the model to the total conductivity, respectively (mho cm^{-1})
K_R	Conductivity of solid (mho-cm^{-1})
$\overline{K}_w$	"Average" conductivity of two solutions in series (Figure 3) (mho cm^{-1})
K_w	Conductivity of solution (mho-cm^{-1})
R_{mf}	Resistivity of mud filtrate (ohm-cm)
R_0	Resistivity of porous medium (ohm-cm)
R_R	Resistivity of solid (ohm-cm)
$\overline{R}_w$	Average resistivity of two solutions in series (Figure 3)
R_w	Resistivity of solution (ohm-cm)
R_{X0}	Resistivity of the invaded zone (ohm-cm)
S.P.	Self Potential deflection as measured in well logging (mv)
t^+	Transference number of the cation in the solution
t_R^+	Transference numbers of the cation in a membrane

Primes and double primes refer to the two solutions at the two ends of the porous plug or membrane.

APPENDIX

The potential E_M (mv) across a cation-selective membrane separating two salt solutions 1 and 2 is given by:

$$E_M = 59.2(2t_R^+ - 1) \log \frac{a_1}{a_2} \tag{24}$$

where a_1 and a_2 are the mean activities of the salt in the two solutions, respectively, and t_R^+ is the transference number of the cation in the membrane. For a discussion of this equation see, for instance, Spiegler and Wyllie, in press.

Consider a series arrangement of electrodes, membranes and solutions as in the following:

Calomel electrode | Solution 1 ‖ Membrane 1 ‖ Solution 2 ‖ Membrane 2 ‖ ...

Solution ... $(n-2)$ ‖ Membrane $(n-2)$ ‖ Solution $(n-1)$ ‖ Membrane $(n-1)$ ‖ Solution n | Calomel electrode.

The total potential difference, E_{total} between the calomel electrodes is equal to the algebraic sum of the membrane potentials:

$$\begin{aligned} E_{total} &= (E_M)_1 + (E_M)_2 + \cdots + (E_M)_{n-2} + (E_M)_{n-1} \\ &= 59.2\left[(2t_{R1}^+ - 1) \log \frac{a_1}{a_2} + (2t_{R2}^+ - 1) \log \frac{a_2}{a_3} + \cdots \right. \\ &\qquad \left. + (2t_{R(n-2)}^+ - 1) \log \frac{a_{(n-2)}}{a_{(n-1)}} + (2t_{R(n-1)}^+ - 1) \log \frac{a_{(n-1)}}{a_n}\right]. \end{aligned} \tag{25}$$

The quantities t_{R1}^+, t_{R2}^+, $\cdots$ $t_{R(n-2)}^+$ and $t_{R(n-1)}^+$ are the transference numbers of the cations in the first, second $\cdots$, $(n-2)$th, and $(n-1)$th membrane. In general, these transference numbers depend on the concentrations of the solutions in contact with the membranes because some of the salt in the solution penetrates into the membrane ("Donnan effect"). The total potential difference between the calomel electrodes depends therefore on the concentration distribution between the membranes.

However, if the membranes are all ideal (i.e., if the "Donnan effect" is negligible) $t_R^+ = 1$ for all membranes and equation (25) reduces to:

$$E_{\text{total}} = 59.2\left[\left(\log\frac{a_1}{a_2} + \log\frac{a_2}{a_3} + \cdots + \log\frac{a_{(n-2)}}{a_{(n-1)}} + \log\frac{a_{(n-1)}}{a_n}\right)\right] = 59.2\log\frac{a_1}{a_n}.$$

The total potential difference between the calomel electrodes depends then only on the activities of the terminal solutions, 1 and n, respectively and not on those in the middle compartments. The whole stack of membranes acts, therefore, like a single cation-selective ideal membrane (equation (1)).

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NON-TECHNICAL PAPERS

GEOPHYSICAL ACCIDENT FACTS—1954*

BART W. SORGE†

ABSTRACT

The safety performance of the geophysical industry did not improve during 1954 as expected. In addition, the participation of geophysical operators in the common endeavor to further safety and accident prevention did not increase. These facts represent a serious challenge to the SEG Standing Committee on Safety. Ways and means must be found to secure increased participation of geophysical operators to insure industry-wide improvement in safety and accident prevention. Safety efforts result in substantial financial savings due to decreased insurance costs and equipment maintenance expenses.

INTRODUCTION

The SEG Committee on Safety has just concluded four years of intensive effort to interest geophysical operators to join in a common endeavor to improve safety and accident-prevention standards to an acceptable level. This effort on the part of the committee has been both a success and a failure.

It has been a success because the committee has been able to interest many organizations in paying more attention to safety and making a greater effort to provide safer working conditions on geophysical field parties. This has resulted in an improved safety record when compared with that of prior years. Among the companies participating in the effort the improvement was so considerable that the Society of Exploration Geophysicists received an "Association Safety Award" from The National Safety Council during the year 1954.

The committee's efforts have also been somewhat of a failure due to the fact that even after four years it has not been possible to interest more than one-third of the geophysical organizations to participate in the common effort. Difficulties have also been encountered in sustaining the interest of some of those participating. As a result, the safety statistics gathered during 1954 by the committee, The National Safety Council, and the American Petroleum Institute show that the industry's safety performance dropped back to what it was during 1952 instead of showing further improvement as was expected.

THE RESPONSIBILITY FOR SAFETY

There is no denying that safety and accident prevention efforts on geophysical field parties are the responsibility of geophysicists. As pointed out in a previ-

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ous paper (Sorge, 1954), geophysicists represent management on geophysical field parties and are responsible for the conduct of the survey work done. They control work procedures and working conditions which are either safe or unsafe, depending on the interest on the part of those responsible.

The SEG is the sole organization to which the majority of exploration geophysicists belong and, therefore, it is logical that one of its committees should further the solution of safety problems in the industry.

To provide safe working conditions for employees is not only a moral responsibility but is also an obligation that we owe to management. A well-functioning safety program results in a material increase of profits from operations. An often used formula states that any ten percent decrease in the occurrence of accidents results in a direct saving of at least $1,500 per one hundred employees. This means that savings in excess of a million and a half dollars have resulted in the geophysical industry due to the improvement in safety performance since 1951.

THE SAFETY RECORD

The safety record of the industry from 1951 to the present is shown in Table 1. The accident frequency is the number of accidents per million man hours which resulted in lost time (beyond the day on which the injury occurred) and the severity is the number of days lost as a result of such accidents per one thousand man hours worked. These definitions of frequency and severity are used universally throughout industry in judging safety performance.

When evaluating the information as given in Table 1, it is well to keep in mind that it represents an average of only one-third of the total number of geophysical organizations. It is reasonable to assume that the other two-thirds of the operators, who do not report their safety experience, do not enjoy any better safety record than that shown. Extremely large variations in performance exist in these averages. For larger geophysical operators, the accident frequency varied between 85.4 and 0.61, and in the case of the smaller operators (those with less

TABLE 1

SAFETY RECORD BY INDUSTRY

Frequency	1951	1952	1953	1954
All Industry	9.06	8.40	7.44	N.A.
Petroleum Industry	10.50	9.67	9.00	7.97
Exploration Section	23.33	14.18	12.40	12.79
Contract Geophysical	53.50	27.80	21.50	26.80
Severity	**1951**	**1952**	**1953**	**1954**
All Industry	.97	.88	.83	N.A.
Petroleum Industry	1.29	1.04	1.08	.79
Exploration Section	1.486	.74	1.00	.67
Contract Geophysical	2.106	1.71	.753	1.54

TABLE 2

TYPES OF VEHICLES INVOLVED IN ACCIDENTS

	1952		1953		1954	
	Number of Accidents	Per Cent of Total	Number of Accidents	Per Cent of Total	Number of Accidents	Per Cent of Total
Not Specified	57	23%	31	14%	62	26%
Cars	53	22%	71	33%	89	37%
Pickups (Survey)	54	22%	36	17%	9	4%
Water Trucks	32	13%	25	12%	25	10%
Drills	22	9%	20	9%	24	10%
Recording Trucks	15	6%	14	7%	14	6%
Shooting Trucks	13	5%	18	8%	17	7%
Total	246	100%	215	100%	240	100%

than 100,000 man hours per year) the variation is even greater, namely between 175 and zero.

THE GEOPHYSICAL ACCIDENT INFORMATION EXCHANGE

The Geophysical Accident Information Exchange provides useful information to all its participants as to the types of accidents, accident causes, and distribution of accidents among the work force. This information for previous years was published in an earlier report (Sorge, 1954, p. 533–538).

Vehicular Accidents

Table 2 shows the types of vehicles involved in accidents, as well as the total number. It can be noted that the percentage of accidents involving cars has increased from year to year. This is apparently due to an increase in the number of prospects that are being worked long distances away from operating bases, so that more personnel transportation vehicles must be used.

The problem becomes still more critical when one considers the information

TABLE 3

CAUSES OF VEHICULAR ACCIDENTS

Type of Accident	1951*	1952	1953	1954
Excessive Speed	30%	21%	22%	23%
Backing	21%	19%	14%	12%
Intersection	13%	12%	9%	10%
Equipment Failure	6%	7%	5%	8%
Passing	4%	21%	17%	10%
Explosives		2%	0%	0%
Collision or Upset			13%	12%
Miscellaneous	18%	14%	13%	25%
Total Number of Accidents	132	246	215	240

* 7 months.

given in Table 3, which indicates that excessive speed is still far in the lead as a cause for vehicular accidents. It will require considerable effort, particularly in education of drivers, to reduce losses resulting from vehicle operations.

Among the many reports submitted to the Geophysical Accident Information Exchange, an unusually large number report collisions between vehicles and cattle, and some between vehicles and children. Many of these accidents could have been avoided by slower driving speeds. Fortunately, the three children involved in accidents were not seriously hurt; however, most of the cattle had to be destroyed.

Personal Injuries

Table 4 shows the distribution, as well as the total number, of personal injury accidents from 1951 through 1954. It is gratifying to note that the percentage of accidents involving drillers and their helpers has continued to decrease during 1954. From the information shown, it appears that the shooter and his helpers

TABLE 4

ACCIDENT RECORD BY OCCUPATION

Type of Job	1951*	1952	1953	1954
Drillers	37%	43%	39%	32%
Recorders	15%	14%	19%	21%
Surveyors	12%	13%	16%	13%
Shooters	10%	10%	8%	11%
Others	26%	20%	18%	23%
Total Accidents	497	1,086	1,139	986

* 7 months.

are less often injured in accidents than any others on a field party. This is further substantiated by the information shown in Table 5, which shows the types of injuries suffered and, in some cases, the factors that were responsible for the accidents. It can be noted that the number of accidents due to the handling of dynamite and caps is extremely small, usually being less than one percent in each of the years of record. This indicates that where recognized danger exists and the need for safety is obvious, safe operations result.

As in previous years, hand injuries continue to lead all others. Similarly, strains and sprains and eye injuries continue respectively in second and third place. In fact, these three types of injuries account for over half of all that occur. It appears, therefore, that anyone making a serious effort to reduce accidents will achieve best results by concentrating his effort on the avoidance of these injuries.

Considering all of the information in Table 5, it becomes apparent that there is a monotonous repetition from year to year in the distribution of types of accidents. It will be one of the prime endeavors of the SEG Committee on Safety to try to improve this situation during the coming year.

TABLE 5

OCCURRENCE OF DIFFERENT TYPES OF PERSONAL INJURIES

	1951*	1952	1953	1954
Total Injuries	497—100%	1,086—100%	1,139—100%	986—100%
Lost Time Injuries	153— 31%	371— 34%	325— 35%	275— 28%
Hand Injuries	21%	25%	27%	25%
Strains & Sprains	14%	17%	15%	20%
Eye Injuries	9%	10%	12%	11%
Collision or Upset	8%	2%	1%	3%
Falls	7%	5%	6%	8%
Moving Vehicles	6%	7%	7%	5%
Sharp Instruments	5%	1%	4%	3%
Falling Objects	5%	7%	6%	5%
Dermatitis	5%	4%	4%	2%
Cable & Power Reels	4%	½%	1%	1%
Infections	3%	2%	1%	2%
Dynamite & Caps	½%	½%	½%	1%
Burns		2%	1½%	2%
Miscellaneous	13%	17%	14%	12%

* 7 months.

Table 6 shows the relationship between types of injuries for various job classifications in terms of number of days lost. The number of days lost for any injury is usually indicative of the seriousness of the accident.

Ignoring a traffic fatality involving a surveyor, the results indicate that drillers and their helpers not only have the largest number of accidents but also lose more time from work than those in any of the other job classifications.

Strains and sprains cause more lost time than any other type of injury, and most of them resulted from improper lifting. Compensation insurance records show that these accidents are also the most costly.

These figures indicate that anyone seriously interested in improving the safety performance of a geophysical field party would do well to concentrate on drillers and their helpers and on the avoidance of strains and sprains.

TABLE 6

NUMBER OF DAYS LOST IN 1954 BECAUSE OF DIFFERENT TYPES OF ACCIDENTS OR INJURIES

Type of Injury	Drillers	Recorders	Surveyors	Shooters	Others	Total
Strains & Sprains	262	207	28	121	68	686
Hand Injuries	330	15	12	5	78	440
Collision or Upset	204	8	7	24	35	278
Moving Vehicles	29	134	6,005	88	10	6,266
Falling Objects	68	2	42	29	5	146
Dynamite & Caps	0	0	0	71	0	71
Others	452	173	211	71	277	1,184
Total	1,345	539	6,305	409	473	9,071

TABLE 7

TYPES OF STRAINS REPORTED TO INFORMATION EXCHANGE

Type of Strains	Total	Lost Time	Days Lost
Lifting	76	34	301
Awkward Position	32	11	115
Falls & Slips	44	19	102
Pulling or Pushing	14	8	85
Others	31	9	83
Total	197	81	686

Improper lifting was responsible for nearly half of the total time lost due to strains and sprains; this is shown in Table 7. This has been true for each of the years since 1951.

Details on the causes of hand injuries are shown in Table 8. Moving machinery, in most cases drilling machinery, is responsible for the largest number of days lost. The breaking of tool joints and the handling of drill pipe, both operations involving drillers and their helpers, were also responsible for a large number of injuries.

The common pipe wrench continues to be the culprit which, when improperly handled, causes many of the injuries. A large number of operators have put into use break-out tongs in order to decrease hand injuries, but unfortunately many of the field party personnel still prefer to use pipe wrenches, even though they are not as safe. It appears that management must insist that pipe wrenches not be used unless absolutely necessary.

A further topic of interest is the relationship between experience and accidents. A survey conducted by the Committee on Safety about a year ago resulted in the conclusion that a new, inexperienced worker is much more likely to be hurt than the experienced hand who knows his job. Accordingly, it is advantageous for the geophysical operator to pay particular attention to new employees and spend time giving them safety training *before* they go to work. This definitely will decrease the number of accidents on a geophysical field party.

TABLE 8

CAUSES OF HAND INJURIES REPORTED TO INFORMATION EXCHANGE

Type of Hand Injuries	Total	Lost Time	Days Lost
Moving Machinery	21	4	87
Breaking Tool Joints	48	18	253
Handling Drill Pipe	18	2	17
Sharp Instruments	19	3	16
Moving Vehicles	6	0	0
Others	134	13	67
Total	246	40	440

Summary

To summarize the information contained in the tabulated results of the Geophysical Accident Information Exchange, a conscientious geophysical operator who seriously wishes to improve the safety performance of his field parties should take the following action:

1. Give new employees better and more thorough safety training before permitting them to work.
2. Concentrate safety effort on drillers and their helpers in order to reduce the number of injuries.
3. Pay particular attention to the proper methods of lifting and to the reduction of hand, back, and eye injuries.
4. Emphasize safe driving of cars through better driver training.
5. Be persistent in the safety effort.

SAFETY EFFORTS RESULT IN FINANCIAL SAVINGS

Safety pays off; it is worthwhile and results in larger profits for management. The Safety Committee has been given information which shows by examples that safety effort is a profitable effort.

Company A, prior to safety effort, paid a penalty on its compensation insurance of $13,000 in 1950. After one year's extensive effort, instead of paying a penalty it received a refund of $9,000. In 1952 this refund increased to $11,700, and increased further to $30,200 in 1953. It is expected that the refund for 1954 will be a similar amount. Therefore, this company, as a result of a serious safety effort, was able to save an amount in excess of $100,000 during a four-year period, certainly a worth-while addition to profits in any organization.

Company B in 1950 paid a two-hundred percent surcharge above normal rates on its compensation insurance. This surcharge dropped to forty percent in 1951, to zero in 1952, and reversed to a credit of thirty-five percent in each of the years 1953 and 1954. As a result of a five-year safety effort, this company was able to save, and add to its earnings, an amount in excess of $200,000, all due to its having instituted an aggressive and active accident prevention program.

Company C suffered $15,000 damages due to truck accidents in 1952 and at the same time incurred 120 lost-time personnel injuries. After two years of intensive effort, the costs due to truck accidents were reduced to $5,000, and the lost-time personnel injuries were reduced to thirty. It is estimated that this effort over a two-year period increased this company's earnings by about $50,000.

Company D has enjoyed a good safety record for several years and is presently enjoying over a million and a half man hours without a lost-time personnel injury. This company feels that its safety effort has increased its earnings between $30,000 and $40,000 per year due to savings in compensation insurance premiums alone. As a useful by-product, much greater savings have been realized on account of more careful operation of the trucks and geophysical equipment, resulting in materially lower maintenance costs.

CONCLUSION

The cooperative safety effort during the last few years has provided the information needed for the geophysical industry to attack intelligently the accident prevention problem. The major causes of poor safety performance are now known and, as a result, successful solution of these problems now depends only on the willingness of geophysical operators to apply the needed effort. To make really worth-while improvement, an industry-wide effort will be necessary.

The members of the Standing Committee on Safety of the Society have and will always stand ready to aid in every way to achieve the desired goal. It is hoped that eventually work on a geophysical field party will be no more dangerous than many occupations presently considered to be much safer.

Only by continued perseverance and determination can the geophysical industry achieve this goal.

REFERENCE

Sorge, B. W., 1954, Safety is our responsibility: Geophysics, v. 17, p. 529–540.

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ANNUAL REPORT OF THE STANDING COMMITTEE ON EDUCATION OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS*

In accordance with the decision of the Council of the Society, the Committee circulated another questionnaire to all institutions which had sent affirmative replies to previous questionnaires or were known to have introduced geophysical courses into their curriculum. The questions covered current courses and enrollments from the 1954 summer session to the present and degrees from July 1, 1953 to June 30, 1954. At the request of a number of Society members, questions were introduced on current scholarships and fellowships and on fields of employment entered by 1954 graduates. The results of the tabulation of replies are presented in Tables I–III. A total of 80 institutions had sent affirmative replies.

The number of undergraduate majors in all fields of geophysics totals 570 and the number of graduate majors 467. There are 9 departments with titles embracing geophysics and 12 departments restricted to meteorology. A total of 210 bachelor's degrees were conferred by 24 institutions and 107 master's degrees by 27 institutions in the year July 1, 1953, to June 30, 1954. A total of 26 Ph.D. degrees were granted by 11 institutions as follows:

University of California (Berkeley)	1
University of California (La Jolla)	1
California Institute of Technology	1
Colorado School of Mines	2
Harvard University	3
Massachusetts Institute of Technology	5
New York University	1
University of Oklahoma	1
Pennsylvania State University	4
Saint Louis University	3
University of Toronto	4

TABLE I

* Presented to the Executive Committee of the Society at its meeting in New York, New York, March 31, 1955, by Reverend James B. Macelwane, S. J., Chairman of the Education Committee. The other members of the Committee are: Perry Byerly, Beno Gutenberg, John C. Hollister, M. King Hubbert, Sherwin F. Kelly, D. C. Skeels, and H. W. Straley, III.

TABLE I

Institution	Administration		Titles of Geophysical Degrees	Degrees Conferred July, 1953–June, 1954			Faculty Teaching Courses in Geophysics
	Departments	Schools or Colleges		Bachelors	Masters	Doctors	
Alaska, U. of	Geophysics	—	B.A., M.A., Ph.D.	—	—	—	2
Alberta, U. of	Physics	—	—	—	—	—	1
Arizona, U. of	Geology, Mining Engineering, Physics	Mines, Liberal Arts	—	—	—	—	3
Arkansas, U. of	Physics, Geology	Arts & Science	—	—	—	—	2[1]
Brigham Young U.	Geology & Geological Engineering	Engineering & Physical Science	—	—	—	—	1
Calif., U. of (Berkeley)	Geological Sciences	—	A.B.,[2] M.A.,[2] Ph.D.[2]	4	5	1	3
Calif., U. of (Los Angeles)	Geology, Physics, Meteorology	Letters & Science	B.A., M.A., Ph.D.	3	1	—	5
Calif., U. of Scripps Inst. of Ocean.	Oceanography	—	M.S.,[3] Ph.D.[3]	—	1[3]	1[3]	4
Calif. Inst. of Tech.	Division of Geological Sciences	—	B.Sc.,[4] M.Sc.,[5] Geophysical Engineer, Ph.D.	—	3	1	5
Southern Calif., U. of	Geology	Letters Arts & Science	—	—	—	—	2
Chicago, U. of	Meteorology	Physical Sciences	B.S.,[6] M.S.,[6] Ph.D.[6]	—	11	—	6
Colorado A & M Coll.	Civil Engineering, Geology	—	—	—	—	—	1
Colorado Sch. of Mines	Geophysics	—	Geophysical Engineer, M.S., D.Sc.	17[7]	2	2	4
Cornell U.	Agronomy, Division of Meteorology	Agriculture	M.S.	—	—	—	1
Dalhousie U.	Physics	—	B.S., B.S.,[8] M.S.	—	1	—	1
Drake U.	Geology, (Meteorology Only)	Liberal Arts	—	—	—	—	1
Florida State U.	Meteorology	Arts & Science	B.S.,[9] M.S.,[9] Ph.D.,[9] M.S.[10]	4	5	—	7
Franklin & Marshall Coll.	Geology	—	—	—	—	—	1
Georgia Inst. of Tech.	Geology	Aeronautical Eg., Ceramic Eg., Civil Eg., Engineering	B.S.[11]	1	—	—	3
Harvard U.	Division of Geological Sciences	—	M.A., Ph.D.	—	—	3	2
Houston, U. of	Interdepartmental Physics, Geology, Mathematics	Arts & Sciences	B.S.[12]	—	—	—	2
Illinois, U. of	Geology, Mining & Metallurgical Engineering	Liberal Arts, Engineering	—	—	—	—	1
Indiana U.	Geology	Arts & Sciences	B.A., B.S., M.A., Ph.D.	4	1	—	1
Iowa State Coll.	Physics, Agronomy	Science, Agriculture	—	—	—	—	4
Johns Hopkins U.	Geology, Civil Eg., Oceanography	Arts & Sciences, Engineering	M.A., Ph.D., M.S.[13]	—	5[14]	—	7
Kansas U.	Geology & Geological Engineering	Liberal Arts, Engineering	—	—	—	—	2
Kansas, U. of	Geology	—	—	—	—	—	—
Kansas City, U. of	Geology & Geography, Physics	Liberal Arts & Science	—	—	—	—	2
Kansas State Coll.	Geology-Geography	—	—[15]	2	—	—	1
Lehigh U.	Mining Engineering	Engineering	B.S.[16]	1	—	—	1
Southwestern Louisiana Inst.	Geology	Engineering	—	—	—	—	—
Manhattan Coll.	Civil Engineering	—	—	—	—	—	1
Marshall Coll.	Geology	Liberal Arts	—	—	—	—	1
Mass. Inst. of Tech.	Meteorology, Geology & Geophysics	—	B.S.,[17] M.S.,[17] Ph.D.,[17] B.S.,[18] M.S.,[18] Sc.D.,[18] Ph.D.[18]	10[19]	12[20]	5[21]	10
Michigan, U. of	Civil Engineering, Geology	Literature, Science & Arts, Engineering	—	—	3	—	5
Michigan Coll. of M. & T.	Physics	—	M.S.[22]	—	1	—	2
Michigan State Coll.	Physics	Science & Arts	—	—	—	—	1
Minnesota, U. of	Geophysics	Mines	Bachelor of Geophysics,[23] M.S.	1	1	—	1
Missouri Sch. of Mines & Metal.	Geology	—	—	—	—	—	2
Montana Sch. of Mines	Physics	—	—	—	—	—	1
Nebraska, U. of	Civil Engineering	Engineering & Architecture	—	—	—	—	1
New Mex., U. of	Geology	—	—	—	—	—	1
New Mexico Inst. of M & T	Physics & Geophysics	Graduate	B.S.,[24] M.S.,[25] Ph.D.	1	2	—	2
City Coll. of N. Y.	Geology	—	B.S.	7[26]	—	—	3
New York U.	Meteorology & Oceanography, Geology	Engineering, Graduate	B.Sc., M.Sc., Ph.D.	3	12	1	9
North Carolina, U. of	Geology & Geography	—	—	—	—	—	1
North Dakota, U. of	Geology	Engineering	—	—	—	—	2
Northwestern U.	Geology	Liberal Arts	—	—	—	—	1

TABLE I—*Continued*

Institution	Administration		Titles of Geophysical Degrees	Degrees Conferred July 1953–June 1954			Faculty Teaching Courses in Geophysics
	Departments	Schools or Colleges		Bachelors	Masters	Doctors	
Oberlin Coll.	Geology & Geography	—	—	—	—	—	—
Ohio State U.	Geology, Physics	Arts & Sciences	B.S.,[27] M.S.,[27] Ph.D.[27]	3	2	—	8
Ohio Wesleyan U.	Geology & Geography	Liberal Arts	—	—	—	—	1
Oklahoma, U. of	Physics, Geology	Arts & Science, Engineering, Graduate	B.S.[28]	—	—	1[29]	3
Oklahoma A & M Coll.	Meteorology, Physics, Mechanical Engineering	Education, Arts & Sciences, Engineering	—	—	—	—	6
Oregon State Coll.	Physics	Science	—	—	—	—	—
Pennsylvania State U.	Geophysics & Geochemistry, Meteorology	Mineral Industries	B.S., M.S., Ph.D., B.S.,[30] M.S.,[30] Ph.D.[30]	53[31]	12[32]	4[33]	13
Pittsburgh, U. of	Geology	Liberal Arts	—	—	—	—	2
Princeton U.	Geological Engineering	—	B.S.,[34] M.S.[34]	2	1	—	1
Redlands, U. of	Geology	—	B.S.[35]	6	—	—	1
Rensselaer Poly. Inst.	Geology	—	B.S.[36]	2	—	—	1
Rutgers U.	Meteorology	Agriculture	M.S.	—	1	—	2
Saint Louis U.	Geophysics & Geophysical Engineering, Electrical Engineering, Engineering	Institute of Technology, Graduate	B.S.,[37] M.S.,[38] Ph.D.,[38] B.S.,[39] M.S.[40]	10[41]	6[42]	3	11
San Jose State Coll.	Physical Science	—	—	—	—	—	3
Saskatchewan, U. of	Physics	—	—	—	—	—	1
Southern Methodist U.	Geology	Arts & Sciences	—	—	—	—	1
Tennessee, U. of	Geology-Geography	—	—	—	—	—	1
A & M Coll. of Texas	Oceanography, Geology	Arts & Sciences, Engineering	B.S.,[43] M.S.,[43] M.S.,[44] Ph.D.,[44] B.S.,[45] M.S.,[45] Ph.D.[45]	4[45]	2	—	17
Texas Christian U.	Physics	Arts & Science	—	—	—	—	2
Texas Tech. Col.	Geology	—	—	—	—	—	—
Toronto, U. of	Physics	Faculties of Arts & Engineering	B.A.,[46] M.A.,[46] Ph.D.	4	7	4	4
Tulane U.	Geology	Arts & Science	—	—	—	—	1
Tulsa, U. of	Physics & Geophysics	Petroleum Science	B.S.,[47] M.S.[48]	6	—	—	1
Utah, U. of	Geophysics, Meteorology	Mines & Mineral Industries	B.S.,[49] M.S.,[49] Ph.D.,[49] B.S.,[50] M.S.	56[51]	1	—	5
Valparaiso U.	Geography-Geology	Liberal Arts	—	—	—	—	1
Virginia Poly. Inst.	Geology	Engineering	—	—	—	—	—
Washington U.	Geology & Geological Engineering	Graduate, Engineering	—	—	2	—	2
Washington, U. of	Oceanography, Geology & Meteorology	—	B.S., M.S., Ph.D.,	—	1	—	3
Wayne U.	Geology	Liberal Arts	—	—	—	—	2
Western Ontario, U. of	Geology & Physics	Arts & Science	B.Sc.,[52] M.Sc.,[52] M.Sc.,[53] Ph.D.[53]	—	—	—	1
West Virginia U.	Physics	Mines	—	—	—	—	2
Wisconsin, U. of	Geology, Meteorology, Civil Eg.	Letters & Science, Engineering	B.S., M.S., Ph.D.	6	6	—	7

[1] Each teaching ½ of a one semester course.
[2] In Geophysics.
[3] In Oceanography
[4] (Geophysics Option).
[5] In Geophysics.
[6] In Meteorology.
[7] Geophysical Engineer.
[8] In Engineering Physics.
[9] In Meteorology.
[10] In Physical Oceanography.
[11] In Physics (Geophysics Option).
[12] (Geophysics curriculum indicated on transcript.)
[13] In Engineering—Given to Students in Meteorology-Hydrology.
[14] Three in Meteorology, Two in Oceanography.
[15] Physical Science (Geophysics Option).
[16] In Mining Engineering (Engineering Geophysics Option).
[17] In Meteorology.
[18] In Geophysics.
[19] Three in Geophysics, Seven in Meteorology.
[20] Two in Geophysics, Ten in Meteorology.
[21] Three in Geophysics, Two in Meteorology.
[22] In Geophysics.
[23] Five Year Undergraduate Curriculum.
[24] In Geophysics.
[25] In Earth Science.
[26] Meteorology.
[27] In Geodetic Science.
[28] In Geology (Geophysical Interpretation Option).
[29] In Geology (Major Subject: Well Logging Methods).
[30] In Meteorology.
[31] Five in Geophysics, Forty-eight in Meteorology.
[32] Three in Geophysics, Nine in Meteorology.
[33] Two in Geophysics, Two in Meteorology.
[34] In Engineering.
[35] In Geology.
[36] In Geology (Geophysics Option).
[37] In Geophysical Engineering.
[38] In Geophysics.
[39] In Professional Meteorology.
[40] In Meteorology.
[41] Seven in Geophysical Engineering, Three in Professional Meteorology.
[42] Three in Geophysics, Three in Meteorology.
[43] In Meteorology.
[44] In Oceanography (Physical, Chemical, Biological, Geological, and Meteorological)
[45] In Geology (Geophysics Option).
[46] Arts and Applied Science.
[47] In Geophysical Engineering.
[48] In Geophysics.
[49] In Geophysics.
[50] In Meteorology.
[51] Fifty-three in Meteorology, Three in Geophysics.
[52] In Geology (Geophysics Option).
[53] In Physics (Geophysics Option).

TABLE II

Institution	Students in Applied Geophysics				Undergraduate Scholarships in Geophysics Granted 1954–55	Graduate Fellowships or Assistantships in Geophysics, 1954–1955			Fields of Employment Entered by 1953–54 Graduates
	Total in Courses 1954–1955		Majors						
	I	II	Undergraduate	Graduate		Pre-Masters	Post-Masters	Post-Doctorate	
Alaska, U. of	4	4	1	3	—	1	1	—	—
Alberta, U. of	5	5	—	—	—	—	—	—	—
Arizona, U. of	8	25	—	—	—	—	—	—	—
Arkansas, U. of	—	7	1	5	—	—[a]	—	—	—
Brigham Young U.	—	6	—	—	—	—	—	—	Geophysics
Calif., U. of (Berkeley)	43	38	15	8	—	—	2	—	Petroleum; Geological Survey (1)
Calif., U. of (Los Angeles)	16	12	12	4	—	2	2	—	Geophysical Prospecting
Calif., U. of Scripps Inst. of Ocean.	11	10	—	14	—	1	2	—	Remained at Scripps
Calif. Inst. of Tech.	24	40	2	12	—	3	4	1	Teaching & Research (1); Industry (2); Graduate Work (1)
Southern Calif., U. of	8	9	—	—	—	—	—	—	—
Chicago, U. of	27[b]	21	3	21	—	6[c]	4	—	Institutional Research Projects; U.S. Weather Bureau
Colorado Sch. of Mines	27	83	111	11	10	4	1	—	Oil & Mineral Geophysical Exploration; Geophysical Research
Cornell U.	—	40	—	—	—	—	—	—	—
Dalhousie U.	—	—	—	1	—	—	—	—	Graduate Work
Drake U.	17	15	—	—	—	—	—	—	—
Florida State U.	279	225	15	42	—	11	5	—	Military; U. S. Weather Bureau; Government Contractors
Franklin & Marshall Coll.	—	10	—	—	—	—	—	—	Geology
Georgia Inst. of Tech.	21	19	15	—	—	—	—	—	Petroleum
Harvard U.	5	2	—	7	—	—	1	—	—
Houston, U. of	18	14	4	—	1	—	—	—	—
Illinois, U. of	22	—	—	—	—	—	—	—	Mining; Geology
Indiana U.	5	11	7	5	—	—	—	—	Petroleum
Iowa State Coll.	—	12	—	—	—	—	—	—	—
Johns Hopkins U.	36	15	—	12	—	6	7	1	Industrial Meteorology; Research
Kansas U.	39	—	—	—	—	—	—	—	Geophysical Exploration
Kansas City, U. of	8	—	—	—	—	—	—	—	—
Kansas State Coll.	1	4	—	—	—	—	—	—	—
Lehigh U.	9	8	6	—	—	—	—	—	Geophysical Contracting Company
Manhattan Coll.	90	—	—	—	—	—	—	—	—
Marshall Coll.	13	—	—	—	—	—	—	—	—
Massachusetts Inst. of Tech.	97	44	36	61	—	10	11	1	Weather Forecasting; Meteorological Research; Military; Petroleum; Mining Geophysics
Michigan, U. of	126	157	—	—	—	—	—	—	Engineering
Michigan Coll. of M. & T.	25	24	—	2	—	1	—	—	Mining
Michigan State Coll.	29	—	—	—	—	—	—	—	—
Minnesota, U. of	25	15	9	1	—	—	—	—	Petroleum
Missouri Sch. of Mines & Metal.	18	30	—	—	—	—	—	—	Geophysical Companies; Oil Companies
Montana Sch. of Mines	—	3	—	—	—	—	—	—	—
Nebraska, U. of	—	20	—	—	—	—	—	—	Corps of Engineers; Geophysics (5)
New Mexico, U. of	—	30	—	—	—	—	—	—	—
New Mex. Inst. of M. & T.	10	11	7[d]	4	—	3	1	—	U.S. Army (2); Graduate Study (1)
City Coll. of N. Y.	80	72	21	—	—	—	—	—	U. S. Army (3); USAF (1); College Teaching (1); Graduate Work (4)
New York U.	55	55	10	41	—	25	8	—	Government; Industry; Air Lines; Commercial Seismograph Company

TABLE II—*Continued*

Institution	Students in Applied Geophysics				Undergraduate Scholarships in Geophysics Granted 1954–55	Graduate Fellowships or Assistants in Geophysics, 1954–1955			Fields of Employment Entered by 1953–54 Graduates
	Total in Courses 1954–1955		Majors						
	I	II	Undergraduate	Graduate		Pre-Masters	Post-Masters	Post-Doctorate	
North Carolina, U. of	—	12	—	—	—	—	—	—	—
North Dakota, U. of	—	11	—	—	—	—	—	—	—
Ohio State U.	22	22	6	16	—	3[e]	2	—	Military (2); Forestry (1)
Ohio Wesleyan U.	61	46	—	—	—	—	—	—	—
Oklahoma, U. of	82	60	30[f]	—	—	—	—	—	Geological-Geophysical Co-ordination
Oklahoma A & M Coll.	153	102	—	11	—	—	—	—	Air Weather Service; U. S. Weather Bureau
Pennsylvania State U.	623	642	84	44	2	4	4	—	Military (2); Geological Survey (2); Graduate Work (2); Teaching (1); Petroleum (3); Air Weather Service; Weather Bureau; Research in Government
Pittsburgh, U. of	40	30	—	—	—	—	—	—	Petroleum; A.E. Comm.
Princeton U.	—	11	5	1	—	—	—	—	Ground Water Consulting Firm (1); Geology (1); Graduate Work (1)
Redlands, U. of	20	—	5	—	—	—	—	—	Petroleum Geology; Geophysical Exploration
Rensselaer Poly. Inst.	4	8	6[g]	—	—	—	—	—	Petroleum
Rutgers U.	102	120	—	—	—	—	—	—	Meteorology
Saint Louis U.	192	235	49	44	1	5	1	—	Seismic Exploration (3); Geophysical Exploration (2); Graduate Work (2); U.S.A.F. (6); U. S. Army (1); Air Lines (1); College Teaching (2); Air Weather Service (1); Industry (1)
San Jose State Coll.	78	60	—	—	—	—	—	—	—
Saskatchewan, U. of	30	30	—	—	—	—	—	—	—
Southern Methodist U.	6	—	—	—	—	—	—	—	—
Tennessee, U. of	10	—	—	—	—	—	—	—	—
A & M Coll. of Texas	183	222	24	41	—	10	14	2	Physical Oceanography Research; Graduate Work (1); Petroleum (3)
Texas Christian U.	9	10	10	—	—	—	—	—	Oil Companies
Toronto, U. of	30	30	18[h]	12	—	1	6	1	Government; University; Petroleum & Mining
Tulane U.	10	12	—	—	—	—	—	—	—
Tulsa, U. of	14	23	16	—	—	—	—	—	Petroleum
Utah, U. of	58	93	22	13	—	2	3	—	Petroleum; Mining; U. S. Navy; USAF; Weather Bureau
Valapraiso U.	—	63	—	—	—	—	—	—	—
Virginia Poly. Inst.	—	4	—	—	—	—	—	—	—
Washington U.	15	10	—	4	—	1	1	—	Oil Exploration; Mining
Washington, U. of	10	10	4	1	—	—	—	—	—
Wayne U.	20	9	—	—	—	—	—	—	—[i]
Western Ontario, U. of	8	8	—	3	—	1	—	—	
West Virginia U.	15	3	—	—	—	—	—	—	—
Wisconsin, U. of	125	120	16	23	—	3	5	—	Military; Graduate Study; Industry; Research

[a] One Graduate Assistant is Assigned to Operate the Fayetteville Seismograph Station.
[b] Plus 35 in the Summer.
[c] Plus One United Nations Fellow.
[d] Juniors and Seniors Only.
[e] Plus One Assistant in Geodetic Science.
[f] Ten are Candidates for B.S. in Geology (Geophysical Interpretation Option).
[g] Candidates for B.S. in Geology (Geophysics Option).
[h] Third & Fourth Years Only.
[i] One B.S. in Geology has gone to another University to study for a Ph.D. in Geophysics.

TABLE III

Number of Semester or Quarter Courses Actually Taught, Summer, 1954 to Spring, 1955
E = Elementary Course; A = Advanced Undergraduate Course; G = Graduate Course

Institution	Field Covered by Courses																			
	General Geophysics & Geophysical Theory	Geophysical Electronics & Instrumentation	Geophysical Exploration (Several Methods)	Seismic Exploration	Gravity Exploration	Magnetic Exploration (Including Airborne)	Geochemical Exploration	Electrical & Electromagnetic Exploration	Radioactivity & Nuclear Exploration	Other Geophysical Methods of Exploration	Earthquake Seismology	Geo-Electricity & Ionospherics	Geomagnetism	Geodesy	Hydrology (Not Hydraulics)	Meteorology	Physical Oceanography	Volcanology	Other
Alaska, U. of			1A										3G						
Alberta, U. of	1A		1A																
Arizona, U. of			3E													6E			
Arkansas, U. of	1E																		
	1A																		
Brigham Young U.	3A																		
	3G																		
Calif., U. of (Berkeley)	1E		1A	½A							1½A								
	4G										2G							1G	
Calif., U. of (Los Angeles)	1A																2E		
	1G		2G	1G	1G						1G					2G	12A		
																	8G		
Calif., U. of Scripps Inst. of Ocean.																	1A		1A
																	2G		
Calif. Inst. of Tech.	1E																		
	5G	1A	1A	1G	1G	1G		1G		1A	1A					1A			
Southern Calif., U. of															1G			1G	
Carnegie Inst. of Tech.															1A				
Chicago, U. of																10E			
																10A			
Cincinnati, U. of																1E			
Colorado A & M Coll.															4E	3E			3E
Colorado Sch. of Mines	5A	1A		1A	1A	1A		1A											1A
	1G			1G	1G	1G	2G			1G									1G
Cornell U.																2E			
																1G			
Drake U.																3E			
Florida, U. of																6E			
Florida State U.																3E			
																9A	2A		
																13G	1G		
Franklin & Marshall Coll.	1E																		
Georgia Inst. of Tech.	1E		1E																
	1A		2A										1A		1A				1A
			4G										4G		3G				4G
Georgia, U. of																4E			
																1A			
																1G			
Harvard U.	1A			1A												1G	1E		*
Houston, U. of	6E																		
Illinois, U. of			1E																1A
																			1G
Indiana U.	3E																		
	5A		3A								3G								
	6G																		
Iowa State Coll.			1E													3E			
																6A			
																2G			
Johns Hopkins U.	1E		1E													1E			
															1A	2A			
															2G	2G	3G		
Kansas, U. of			1A																
Kansas City, U. of																8E			
																14A			
Kansas State Coll.	1E	1A																	
Kentucky, U. of																3E			
																3A			
Lehigh U.	1E		1E	½A	½A	½A													
Southwestern Louisiana Inst.															1E	1E			
Manhattan Coll.															1E				1E
Marshall Coll.																1E			
Maryland, U. of												1A†							
Mass. Inst. of Tech.	1E		1E				1E				1E					4E	1E		
	1A		1A						1A							12A			
	1G		1G				1G		1G							10G			
Michigan, U. of	1E		1A																
Michigan Coll. of M. & T.	1E		3A	1A	1G					1A									
Michigan State Coll.	5E															3E			
Minnesota, U. of	1E		1E	1A	½A	½A		1A			1E								
Missouri, U. of																8E			
Missouri Sch. of Mines & Metal.			3E	1E													3E		
			2A																

TABLE III—*Continued*

Institution	Field Covered by Courses																		
	General Geophysics & Geophysical Theory	Geophysical Electronics & Instrumentation	Geophysical Exploration (Several Methods)	Seismic Exploration	Gravity Exploration	Magnetic Exploration (Including Airborne)	Geochemical Exploration	Electrical & Electromagnetic Exploration	Radioactivity & Nuclear Exploration	Other Geophysical Methods of Exploration	Earthquake Seismology	Geo-Electricity & Ionospherics	Geomagnetism	Geodesy	Hydrology (Not Hydraulics)	Meteorology	Physical Oceanography	Volcanology	Other
Montana Sch. of Mines	1E														1A				
Nebraska, U. of																3E			
New Mexico, U. of	1E															4A			
New Mex. Inst. of M. & T.			3E													2E	1E		
	3G		4G													10A			
City Coll. of N. Y.																8G	4G		
New York U.	1G		1G													4E		4E	
North Carolina, U. of			1E													6A			
North Dakota, U. of	3E						4E									1E			1E
Northwestern U.	2E													1E		1E			2A
Ohio State U.	1E													3A		6E			2G
	1A													5G	1G	2E			1E
Ohio Wesleyan U.																4E			
Oklahoma, U. of			3A	1A	1A	1A										7A			
Oklahoma A & M Coll.	4E															6G			
																1E			
Oregon, U. of																3E			
Oregon State Coll.																3A			
	3G										3G					9G			
Pennsylvania State U.	1E														2E	7E			
	3A	2A					1A	2A		1A					1A	9A			
										1G						8G	1G		5G
Pittsburgh, U. of			4E													2E			
Princeton U.			1E																
			1A																
			1G																
Redlands, U. of	1E		1E																
Rensselaer Poly. Inst.	2E																		
	1A																		
Rutgers U.																2E			
																2A			
																3G			
Saint Louis U.	5A	3A	2A								4A			2A	2A	11A			
	5G		1G								4G					9G			
San Jose State Coll.	1E															2E		1E	
																2A			
Saskatchewan, U. of																2E			
South Carolina, U. of																1E			
Southern Methodist U.			1E																
Tennessee, U. of																3E			
East Tennessee State Coll.																9E			6E
A & M Coll. of Texas			1E													6E	1E		
			1A													5A	1A		2A
			1G													3G	7G		9G
Texas Christian U.			1E	1A															
Toronto, U. of	2E		2E																
	2A		2A																
	2G																		
Tulsa, U. of	2E		1A	1A	1A					1A									
Utah, U. of			1E	½E	½E	½E	1E	½E								24E			
				1A	1A	1A		1A	1A		1G		1G	1G		45A			
																30G			
Virginia Poly. Inst.			2E																
Washington U.			1A	1G	1G	1G	1G	1G											
Washington, U. of											1A					13E	2E		
											1G					7A	7A		
																11G	4G	1G	
Wayne U.	2E															1E			
Western Ontario, U. of	1A		1A																
	1G		1G																
West Virginia U.			1E								2E					2E			
Wisconsin, U. of	1E		1E												1E				
	1A	2A													1A	4A	1A		1A
	1G															2G			

* Problems in Geophysics; Research in Seismology; Research in Geophysics.
† Plus Graduate Research in this Field.

DEPARTMENTS

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,708,261. R. R. Thompson. Iss. 5/10/55. App. 12/23/52. Assign. Esso Research and Engineering Co.

Subsurface Areal Electrical Exploration. A method of deep electrical prospecting in which a commutated d-c is passed between an electrode in the well and an electrode on the surface and the potential differences compared between pairs of electrodes on the surface and colinear with the well and equidistantly spaced therefrom.

U. S. No. 2,711,510. D. J. Tricebock. Iss. 6/21/55. App. 6/21/50. Assign. Radio Corporation of America.

Metal Detector Balance Controls. A circuit for balancing a bridge-type metal detector for amplitude and phase by having the two coils connected to the ends of two potentiometers whose respective contacts go to ground and the exciting oscillator, and with condensers connected from one end of each coil to one of the potentiometer contacts.

MAGNETIC PROSPECTING

U. S. No. 2,706,801. W. E. Tolles. Iss. 4/19/55. App. 8/8/44. Assign. U.S.A.

Magnetic Field Compensation System. A system for compensating an airborne magnetometer by using three auxiliary flux-valve elements the cross products of whose outputs are taken, the squares of whose outputs are taken, and the derivative of the output of the vertical compensating element is also taken, all these quantities being added to the output of the magnetic measuring element.

U. S. No. 2,707,769. H. B. Shaper. Iss. 5/3/55. App. 11/3/53. Assign. Dyna-Labs Inc.

Magnetic Field Strength Measuring Devices. A Hall-effect magnetometer using a thin diamond-shaped sheet of bismuth connected in an a-c bridge circuit so that a-c is passed between opposite corners and the Hall-effect voltage generated across the other corners is balanced by voltage from the bridge.

U. S. No. 2,709,783. D. G. C. Hare. Iss. 5/31/55. App. 4/21/44. Assign. U. S. A.

Magnetic Incremometer or Gradiometer. A magnetic gradiometer in which two spaced flux-valve elements are mounted coaxially in a common tubular housing which is continuously rotated on its axis by a motor, the output signal from the flux valves being averaged so as to eliminate errors due to lack of parallelism of the elements.

RADIOACTIVITY PROSPECTING

U. S. No. 2,712, 088. A. Whitman. Iss. 6/28/55. App. 12/10/52. Assign. Tracerlab, Inc.

Radiation Counter and Fill Gas. A self-quenching Geiger-Mueller counter having a pair of electrodes and a gas mixture of helium with a small amount of isobutane and a smaller amount of butadiene.

SEISMIC PROSPECTING

U. S. No. 2,706,011. J. F. Bayhi. Iss. 4/12/55. App. 7/27/50. Assign. Esso Research and Engineering Co.

Seismic Exploration With Shots Above Ground. An air-shooting array using shots in line with a linear detector spread with the shots placed at increasing elevation toward the detectors.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,706,401. C. P. Spaulding. Iss. 4/19/55. App. 12/9/50. Assign. Consolidated Engineering Corp.

Low Frequency Vibrometer. A seismometer having a mass suspended on two leaf springs which make an angle with each other and with the center of gravity of the mass offset from the center of support so that translation induces rotary motion of the mass, or having a pair of eccentrically-mounted masses arranged for opposing rotation and connected by helical springs.

U. S. No. 2,706,805. D. H. Clewell. Iss. 4/19/55. App. 2/11/47 and 11/29/49. Assign. Socony-Vacuum Oil Co. Inc.

Eddy Current Seismometer. A seismometer having a metal strip suspended in the air gap of a stationary magnet excited with a-c and a pair of stationary coils near the strip connected so that emfs from the a-c field are in opposition but the emfs from the eddy-current fields are additive.

U. S. No. 2,707,524. O. C. Montgomery. Iss. 5/3/55. App. 7/31/50. Assign. Phillips Petroleum Co.

Seismic Recording System. A system for firing a seismic shot coincident with a heavy timing line in which the blasting machine energy is fed to a bridge circuit containing the cap through a gas tube which is made conducting by an r-f signal controlled from the recorder by a photocell actuated by the timing-line light impulse.

U. S. No. 2,708,742. W. T. Harris. Iss. 5/17/55. App. 4/22/52. Assign. The Harris Transducer Corp.

Hydrophone Cable. A hydrophone cable array having a central strain cable with electrical conductors around it and annular electrostrictive transducers sensitive to radial pressure impulses located at spaced intervals along the cable.

U. S. No. 2,709,206. H. B. Ferguson. Iss. 5/24/55. App. 1/31/51. Assign. Esso Research and Engineering Co.

Constant Time Delay Band-Pass Filter. A seismograph filter having a series of band-pass sections of increasing but overlapping frequency and constant time delay for all frequencies within the band and adjacent sections having their Q proportional to the peak frequency, the inputs of the sections being in parallel with a phase inverter in alternate sections.

U. S. No. 2,710,070. E. Merten. Iss. 6/7/55. App. 3/26/51. Assign. Shell Development Co.

Seismic Recording. A method of preparing a seismic profile by making a composite of variable-area records and photographing it while moving it a distance required to produce an overlap of a desired number of traces.

U. S. No. 2,710,661. G. M. Webster. Iss. 6/14/55. App. 8/25/51. Assign. Esso Research and Engineering Co.

Method of Compositing Seismic Records. A method of mixing variable-density seismograms by photographing the original record trace by trace through a longitudinal slit so that each trace of the final record is made up of a multiple exposure on adjacent original traces.

U. S. No. 2,712,124. J. R. Ording. Iss. 6/28/55. App. 3/26/48. Assign. Esso Research and Engineering Co.

Seismic Exploration Method and Apparatus. A method of seismic exploration using a magnetostrictive geophone which is responsive to the pressure in a coupling medium such as water and is unresponsive to motion of the geophone.

WELL LOGGING

U. S. No. 2,706,406. R. P. Vincent and H. Schaefer. Iss. 4/19/55. App. 9/23/49. Assign. Stanolind Oil and Gas Co.

Fluid Flowmeter. An impeller-type well flowmeter having caliper arms connected to a brake which retards the impeller in small hole so as to automatically correct the indication for hole diameter.

U. S. No. 2,707,266. H.-G. Doll. Iss. 4/26/55. App. 9/9/53. Assign. Schlumberger Well Surveying Corp.

Systems for Investigating Spontaneous Potentials in Wells. A system for obtaining the self potential emf by establishing an extraneous current flow in the vicinity of the s-p electrode in the well and maintaining a fixed potential at electrodes on each side of the s-p electrode and producing a pulsating pressure variation in the well.

U. S. No. 2,707,768. J. E. Owen. Iss. 5/3/55. App. 7/2/48. Assign. Geophysical Research Corp.

Geophysical Exploration by Electrical Well Logging. An electrical well logging system in which the apparent resistivity and the apparent conductivity of the formations are recorded so that both curves remain entirely on the record, one curve showing detail for low resistivity formations and the other showing detail for high resistivity formations.

U. S. No. 2,708,155. S. E. Buckley and W. D. Mounce. Iss. 5/10/55. App. 4/30/52. Assign. Esso Research and Engineering Co.

Method for Logging Wells. A method of detecting the presence of hydrocarbons in well formations by removing the filter cake, exposing the formation to a strong oxidizing agent which reacts with hydrocarbons present and heats one junction of a thermocouple whose emf is transmitted to the surface and recorded.

U. S. No. 2,708,316. J. V. Fredd. Iss. 5/17/55. App. 7/2/51. Assign. Otis Pressure Control, Inc.

Tubing Caliper. A tubing calipering device having wheels on arms which are spring-pressed against the inside of the tubing and a number of circumferentially-spaced feeler arms which are mechanically connected to a recording stylus.

U. S. No. 2,708,485. C. B. Vogel. Iss. 5/17/55. App. 4/29/52. Assign. Shell Development Co.

Well Logging. An interval velocity logging apparatus using a number of vertically-spaced receivers with alternately-operating spark-discharge transmitters at each end of the array, the received impulses being displayed on a c-r tube screen as two seismograms from the respective sources.

U. S. No. 2,709,753. S. Krasnow and M. J. Test. Iss. 5/31/55. App. 10/1/41 and 1/2/51. Assign. Schlumberger Well Surveying Corp.

Temperature Compensated Bore Hole Radioactivity Apparatus. A radioactivity logging apparatus in which d-c for operating the sensitive element is obtained from a-c fed down the cable and having a temperature responsive element to control the d-c so as to compensate for changes in sensitivity.

U. S. No. 2,710,925. A. S. McKay. Iss. 6/14/55. App. 3/28/52. Assign. The Texas Co.

Radioactivity Bore Hole Logging. A neutron-gamma ray logging method using a source that produces both neutrons and gamma rays and a shield around the detector of such attenuation that changes in detected scattered gamma rays due to variations in borehole diameter compensate for changes in detected induced gamma rays due to variations in borehole diameter.

U. S. No. 2,711,084. R. A. Bergan. Iss. 6/21/55. App. 8/30/52. Assign. Well Surveys, Inc.

Refrigeration System for Well Logging Instruments. A system for refrigerating the scintillation counter and photo-multiplier tube of a radioactivity logging sonde by means of ice in an adjacent compartment, the ice being formed by circulation of a refrigerant through tubing having connections on the outside of the sonde.

U. S. No. 2,711,649. B. M. Baker. Iss. 6/28/55. App. 12/18/50. Assign. Engineering Laboratories, Inc.

Temperature Increment Drive Mechanism for Pressure Recorders. A pressure recorder for lowering into a well and having a pressure-actuated stylus which records on a drum driven by a bi-metallic element through a ratchet so that the drum can rotate in only one direction.

U. S. No. 2,712,081. R. E. Fearon and J. M. Thayer. Iss. 6/28/55. App. 7/30/49. Assign. Well Surveys, Inc.

Method of Neutron Well Logging. A neutron logging method in which the formations are bombarded with fast neutrons, and diffused neutrons within a plurality of selected energy ranges are detected and the pulses converted to a d-c which is recorded at the surface.

MISCELLANEOUS

U. S. No. 2,705,417. P. C. Romo and T. W. Lynch. Iss. 4/5/55. App. 12/21/51. Assign. Petroleum Engineering Associates, Inc.

Mineralogical Analysis. A method of differential thermal analysis in which the reference standard is made to contain one or more constituents known to exist in the sample so that other constituents of the sample may be more readily determined.

U. S. No. 2,705,418. P. P. Reichertz and C. E. Francis. Iss. 4/5/55. App. 12/30/50. Assign. Socony-Vacuum Oil Co., Inc.

Apparatus for Measuring Characteristics of Core Samples Under Compressive Stresses. A core testing apparatus having a piston which enters one end of the core sleeve so that the core specimen can be loaded in compression with a hydraulic press to simulate the effect of overburden, the hydraulic fluid which actuates the press also being applied between the outside of the core sleeve and an outer supporting cylinder.

U. S. No. 2,706,793. L. W. Alvarez, B. Rossi, and F. C. Chromey. Iss. 4/19/55. App. 5/15/46. Assign. U. S. A.

Vertical Determination Device. A device for determining the terrestrial vertical by means of three cosmic ray detectors located at the vertices of a triangle with two pairs connected to coincidence counters whose outputs are compared and the ratio indicated or used to control orienting servo motors.

U. S. No. 2,706,904. K. L. Hertel. Iss. 4/26/55. App. 4/9/51. Assign. University of Tennessee Research Corp.

Apparatus for and Method of Testing Porous Materials. A device for determining the permeability of a porous material in which the pressure of air is measured in a hollow annular nozzle pressed against a flat surface of the material with air flowing from the nozzle both outwardly and inwardly through the material.

U. S. No. 2,709,069. F. G. Boucher. Iss. 5/24/55. App. 4/28/52. Assign. Esso Research and Engineering Co.

Orienting Subsurface Earth Cores In Situ. A device for magnetizing cores in a known azimuthal orientation prior to cutting the core having an electromagnet with pole pieces which contact the bottom of the hole and also a magnetic compass which is clamped by dropping a go-devil which also turns on the electromagnet.

U. S. No. 2,710,169. B. O. Prescott and J. E. Wilson. Iss. 6/7/55. App. 6/16/52. Assign. Shell Development Co.

Method for Determining the Dip and Strike of Formations Traversed by a Borehole. A method of

determining the attitude of formations by cutting side-wall cores in three different known azimuths and at a known angle to the axis of the borehole, the core cutter being guided by a whipstock element whose orientation is known.

U. S. No. 2,710,924. T. J. Morrison, Jr. and P. Galvanek, Jr. Iss. 6/14/55. App. 1/13/54. Assign. American Cyanamid Co.

Fluorimeter. A device for measuring the fluorescence of samples by exposing them close to a source of ultraviolet light and detecting the fluorescence with a photomultiplier tube whose output is indicated by a microammeter.

U. S. No. 2,710,961. J. E. Hawkins. Iss. 6/14/55. App. 6/26/53. Assign. Seismograph Service Corp.

Radio Location System. A phase-comparison type of radio locating system using five stations to transmit six different frequencies, the second and third pairs of stations alternately radiating and also alternately modulating the signals from the first pair of stations.

U. S. No. 2,711,644. E. D. Myers. Iss. 6/28/55. App. 5/28/51.

Apparatus for Determining and Measuring the Gas Content of Soils. An apparatus for measuring the gas content of an impermeable sample having a closed container with de-aerated water in which the sample is mechanically disintegrated after which the amount of gas released is determined from the pressure change observed when a known quantity of gas is introduced into the chamber.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE SECOND QUARTER OF 1955

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2,705,434	416	2,706,755	200	2,707,395	200
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* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

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REVIEWS

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Rapports Scientifiques des Expeditions Polaires Francaises. No. N.III.2. Sondages Seismiques au Groenland. Premiere Partie: Etude des vitesses de propagation des ondes seismiques sur l'Inlandsis du Groenland, Alain Joset et Jean Jacques Holtzscherer, by *Paul Wuenschel*. 957

Seismology, by K. E. Bullen, John Wiley & Sons, Inc., New York, 1954.

This is a pocket-size booklet of 123 pages by an eminent Australian seismologist, intended as a brief introduction to modern seismology for students of science. It contains chapters on instrumental seismology, elastic waves, fitting elastic theory to the earth, seismology and geology, seismic rays and travel times, earth models, microseisms, and notable earthquakes. This work may be warmly recommended as extracurricular reading for the exploration seismologist. He will find here stimulating thoughts and remarks on many matters of interest such as damping and dispersion of waves, aeolotropy, and imperfect elasticity.

The chapter on seismology and geology ties in with current studies by the author on the volume of the strained region prior to the largest earthquakes. The numerical value given in the book, 1,000,000 cubic miles, has been superseded by a lower estimate, 10,000 cubic miles, due to a downward revision of the estimated total energy. (See K. E. Bullen, *Bul. Seism. Soc. of America*, v. 45, p. 43, 1955.)

The author's main interest is in the direct study of seismic waves and the conclusions that may be drawn from them, rather than in the causes of the stresses in the crust. He is ready to doubt the existence of convection currents in the mantle and states in one brief paragraph that the ultimate source of the energy which gives rise to earthquakes is presumably thermal and is generally associated with cooling in the outer 700 km.

F. A. VAN MELLE

Modern Physics for the Engineer, edited by L. N. Ridenour, McGraw-Hill Book Co., Inc., New York, 1954, 499 p., $7.50.

This book contains the lectures presented in an extension course given at the University of California at Los Angeles. The course was organized to appeal to practicing engineers who find themselves so compartmentalized in their professions that they may be oblivious to the progress made in

other fields. The course was organized to acquaint such engineers with recent advances in modern physics, as well as in the ever-expanding field of electronics and the new field of information-processing.

To accomplish this, the course was subdivided into three parts. The first described the laws of nature. Lectures were included here on Relativity and the Foundations of Mechanics, Atomic Structure, Physics of the Solid State, Magnetism, Microwave Spectroscopy, Nuclear Structure and Transmutation, Electronuclear Machines, the Actinide Elements and Nuclear Power, and Elementary Particles. The second part described man's physical environment and included lectures on Astrophysics, High-Pressure Phenomena with Application to Geophysics, The Earth Beneath the Sea, Thunderstorms and the Lightning Strokes, and Transient Phenomena in Supersonic Flow. The last part dealt with "Information and its Communication." These lectures were on Electrons and Waves, Semi-conductor Electronics, Communication Theory and the Transmission of Information, and Computing Machines and the Processing of Information.

Because of the breadth of the coverage, each of the subjects out of necessity was presented in a considerably condensed form. This brevity was offset somewhat by a copious bibliography. Mathematics was not used although the engineer was assumed to be familiar with physics at the undergraduate level. Each of the authors, an authority in his field, organized his presentation to give a brief history of the research and theoretical work thus far accomplished in his field, to state the present status of its development, to indicate the application of his subject to other fields of research, to enumerate its future potentialities, and to predict the direction that future research will take.

The book is a progress report which brings the reader up to date in the various fields it covers. Those in the petroleum industry who work with well logging problems, reservoir problems, or geochemistry should find the book especially valuable. The last part of the book, which is devoted to information theory and computing machines, serves as an excellent introduction to the subject for those who are not familiar with these new tools that have already seen much service in geophysical work.

PAUL WUENSCHEL

Geology in Engineering, John R. Schultz and Arthur B. Cleaves, with a chapter on Soil Mechanics, by E. J. Yoder, John Wiley & Sons, Inc., New York, 1955, 592 p. $8.75.

This book, the latest in a growing list of texts on introductory geology, has been written according to the authors' preface as an attempt to introduce (civil) engineers to those "phases of geology that experience shows to be most useful in their work." As the authors feel that "there is perhaps an even greater need for a book acquainting geologists employed in engineering work with engineering practices," they have included several chapters devoted to this subject. While this reviewer concurs there is a need for such publication, he feels that the authors' admittedly limited attempt to satisfy both needs in a single volume was perhaps a mistake. In order to keep within reasonable bounds as regards length of text, much material had to be treated in a very cursory fashion, and material was omitted that many will feel should have been included. While this book is not intended for a geophysical audience, the inclusion of much material not found in other geologic textbooks, it is believed, will make it on the whole instructive reading for the average geophysicist as well as the civil engineer and geologist.

There are 16 chapters devoted to geology and geologic interpretation and 6 chapters used to describe engineering investigations and procedures dependent upon geologic factors. The authors are to be commended upon their presentation of the historical development of geology, the relation of geology to civil engineering, the common minerals, weathering processes, soils, stream erosion and deposition, desert land forms, beach erosion, glacial movement, frost action in soils, landslides and related phenomena, soils interpretation from aerial photographs, present procedures in soil mechanics, core drilling and geologic problems associated with the construction of dams, reservoirs, foundations, tunnels, highways, airfields and geologic materials used as concrete aggregate. The principal weaknesses lie in the discussion of rocks, structural geology, stratigraphy, historical geology, ground water hydrology, shorelines, geologic interpretation of maps and aerial photographs, and the application of

geophysical methods. In terms of the authors' objectives, only the discussion of earthquakes has been overemphasized since the reviewer feels excessive space has been devoted to this subject.

Only in the presentation on geophysical methods does it appear that the authors have limited knowledge concerning the subject under consideration. The weaknesses in all the other categories listed as being not adequate are related primarily to too cursory a treatment. Some specific examples of weaknesses are as follows: While the use of aerial photographs is considered from the standpoint of recognizing soil types, the recognition of geologic structure is not considered, nor is the value of aerial photographs in studying silting and channel movement in lacustrine or estuarine waters discussed. While base exchange in clays is treated adequately from a chemical standpoint, the effect of this phenomenon on the physical properties of clays is not considered nor is the cause of silting at the salt water-fresh water contact near the mouths of rivers considered although the need for dredging in such areas is mentioned. While the effect of excess soil water is commented upon in frost heaving, the effect of water of dilatency on structural foundations in river valleys and the formation of so-called "quick sands" is not considered. While a very comprehensive treatment is given on concrete aggregates and the importance of grading and chemical coatings is stressed, it is not pointed out that because of these two factors marine beach sands are not suitable for concrete work without treatment.

Other omissions that the authors may have felt involved debatable philosophical considerations and hence purposely omitted include the relationship of the major topographic features of the earth to subsurface crustal structure. However, the internal structure of the earth as determined from earthquake seismology is presented. Isostasy, while mentioned as an explanation of regional tilting, is not defined in terms of either the theories of its nature or the physical evidence for its existence.

The reviewer, as one who has been teaching geology to engineers for over twenty years, feels that this text, while still not ideal, takes a notable stride toward filling a great need, and the authors are to be commended for having rendered their profession a great service. That the authors recognize some of the inadequacies pointed out is evident from the statement in the preface that a supplementary laboratory manual with practical problems and visual aids is a desirable adjunct for use with the text. Fortunately for the teaching profession, it appears that the professor also is still a desirable adjunct.

GEORGE P. WOOLLARD
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"Modellversuche mit seismischen Wellen (Model experiments with seismic waves)" by J. W. Risnitschenko, B. N. Iwakin, and W. R. Bugrow, *"Bergakademie," Zeitschrift für Bergbau, Huettenwesen und verwandten Wissenschaften*, herausgegeben von der Bergakademie Freiberg, v. VI, p. 67–73 and p. 98–109, 1954.

The above is a good German translation of an article which appeared in the Proceedings of the Academy of Sciences of the U.S.S.R. in 1951. It describes seismic model experiments on the approximate scale of 1:1,000, in length as well as time, a scale favored also by many experimenters in this country for work in connection with applied seismology. The authors state that the same apparatus may also be used for problems of earthquake seismology with a scaling factor of the order of 1:100,000.

The interest of the article for the exploration geophysicist and the experimenter lies partly in the fact that it is written as an introduction to model experiments in general. When, for instance, different methods are available for generating a pulse, all are discussed although one might be preferred. Actually, piezoelectric devices were used both for generating pulses and for detection in the 100,000 Hertz range. In their attempt at a general discussion the authors make some reckless statements, for instance that the "period" of the inception of the *P* wave in an earthquake is equal to the duration of the process which causes the earthquake.

The article is accompanied by a list of 69 references up to 1951, over half of them to the Russian literature.

F. A. VAN MELLE

"An Explanation of the Lake Michigan Wave of 26 June, 1954," by M. Ewing, F. Press, and W. L. Donn. *Science*, v. 120, p. 684–686, 1954.

The disastrous six- to ten-foot wave that hit the shore of Lake Michigan over a stretch of more than 70 miles, including the Chicago area, is convincingly explained by the unusual high speed of about 65 mi/hr with which a squall line accompanied by an atmospheric pressure jump of 0.1 inch crossed the south half of the lake from NW to SE early the same day. The theoretical depth for which a long-period wave would be propagated with the speed of 65 mi/hr obtains (according to the formula $h=c^2/g$, where h is the depth of the water, c the speed of the wave, and g the acceleration of gravity) for some 50 miles in a zone along the 300-ft depth contour which runs locally in the same direction traveled by the squall. The Chicago area, where at least seven lives were lost, was hit by the flood wave an hour after the time of its reflection against the southeast shore near the Michigan-Indiana border.

This phenomenon of resonant coupling of a traveling atmospheric disturbance to surface waves has been observed before on the English North Sea coast. An analogous coupling from air waves (explosion sound) to seismic ground roll was studied previously by the senior authors (GEOPHYSICS, v. 16, p. 416, 1951). It lends theoretical support to the explanation offered for the flood wave.

F. A. VAN MELLE

"Early Arrivals in Seismic Prospecting," by F. F. Evison, *Nature*, v. 173, p. 1047, 1954.

The author restates his belief, expressed in previous publications, that electromechanical seismic sources are better suited than conventional explosives for shallow investigations such as are used for foundation and mining problems. As experimental evidence, a record is reproduced which shows the input pulse applied to the shaker (not the outgoing seismic signal just below the shaker) and the output of a detector located 125 feet away in which "the confusion normally found in the early part of a seismic record is absent." It should be pointed out that this "confusion" results from explosive charges large enough to bring out deep reflections, charges which may well be one hundred times heavier than those required for shallow work. Moreover, many of us recall outgoing signals from small conventional charges which, when properly recorded by a well-planted sub-shot detector, closely resemble the simplest possible plane-wave signal, although in fact coming from a point source. The recording of such a displacement in one direction until its return to its original position is equivalent in velocity registration to a positive and a negative loop with equal areas between curve and axis. With proper shooting and recording techniques, such shots are perfectly reproducible. Therefore, the case for the electromechanical source, which is largely limited to surface locations, may not be quite as strong as the author believes.

F. A. VAN MELLE

"A Discussion on the Floor of the Atlantic Ocean," under the leadership of E. C. Bullard, *Proc. Roy. Soc., A*, v. 222, p. 287–407, 1954.

Recent advances in the knowledge of sedimentation in the ocean basins and recent advances in determining the structure of the ocean basins were the subjects for discussion before a panel of geologists and geophysicists meeting under the auspices of the Royal Society of London. With regard to sedimentation, the most dramatic advance has been the recognition of turbidity currents as one of the fundamental sedimentation processes at work in the ocean basins. It was concluded that turbidity currents were responsible for the presence of coarse, shallow-water sediments found in cores taken in deep water. Other examples were cited wherein turbidity currents produced graded bedding in Paleozoic graywackes.

Equally significant is the age and paleoclimatic determinations made on sedimentary cores taken at specific localities in the deep ocean. Wiseman described in detail his CO_2 technique and its favorable comparison to the O^{18} and pollen-analysis techniques for determining paleotemperatures.

The deep structure of the oceans has been studied by using the dispersion of surface waves from

earthquakes when their paths cross the ocean basins, by gravity measurements, and by standard refraction and reflection techniques. Only the latter of these methods was discussed before this panel. The work of Ewing, Raitt, Gaskell, and Hill has given consistently similar results. For measurements over the deep ocean they have found only a thin sedimentary cover ranging in thickness from 0.5 to 1 km lying on rocks whose velocity ranges from 6.3 to 6.6 km/sec. Below this intermediate layer at a depth ranging from 10 to 14 km lies the Mohorovičić discontinuity. This structure is altered near volcanic islands and near transitional zones adjacent to the continents. Near the volcanic islands a velocity of 4.0 to 5.0 km/sec is recorded below the sedimentary layer and the intermediate layer increases in velocity to 6.5–7.0 km/sec. The Mohorovičić discontinuity has not as yet been traced successfully under the oceanic islands. In the transitional zones near the continents an additional, sedimentary layer of velocity 2.5 to 3.3 km/sec is found lying on a basement rock whose velocity (5.0 to 5.8 km/sec) is considered typical of granite or granite-like rock.

A similar oceanic structure can be deduced from gravity measurements at sea and on the continent. To satisfy the observed values a dense rock must lie nearer to the earth's surface under the oceans than under the continents. The seismic evidence indicates that the peridotite layer, a dense rock, is at a depth of 10 to 14 km under the oceans and 25 to 40 km under the continents.

This complete agreement between the gravity and seismic results negates any hypothesis that the oceans are merely foundered continents.

The discussion was very successful because it brought together divergent ideas as to the structure of the oceans and continents. It illustrated very clearly the conflict between an intuitive approach and an experimental approach to the solution of geological problems.

PAUL WUENSCHEL

"Rapports Scientifiques des Expeditions Polaires Francaises. No. N.III.2 Sondages Seismiques au Groenland. Premiere Partie: Etude des vitesses de propagation des ondes seismiques sur l'Inlandsis du Groenland," by Alain Joset et Jean-Jacques Holtzscherer, *Annales de Geophysique*, Tome 9, fascicule 4, Octobre–Decembre 1953, p. 329–344.

This paper reports the seismic observations that were made on the Greenland ice cap and presents the results of the standard calculations performed on these data. The paper would be of interest to students of tectonics because of the factual information that it contains regarding the thickness of the ice and the nature of the rock under the ice. Since this publication may not be readily available, a summary of the results will be given below.

Six seismic refraction spreads and three vertical velocity surveys in boreholes were undertaken. The longest spread was 11 km and this was the only one that was reversed. The remaining five spreads, ranging in length from 0.9 km to 10 km were unreversed. The deepest bore hole was 125 meters.

The velocity of the snow was found to increase gradually with depth. At one locality, its velocity at 13 meters depth was 1,540 m/sec and at 63 meters it was 3,380 m/sec. The mean velocity of the ice ranged from 3,800 m/sec to 3,950 m/sec. The lower value was obtained near the periphery at low elevations while the larger value was obtained near the center of the ice cap at slightly higher elevations. Shear waves propagating through the ice were also recorded. The ice was 600 meters thick within 25 km of the periphery and over 3,000 meters thick at the center of the cap.

In the long reversed spread, three refracting horizons below the ice cap were recorded. The velocities of these horizons were 5,000 m/sec, 5,450 m/sec, and 6,650 m/sec, respectively. The first two were true velocities and the last was an apparent velocity. The thicknesses of the ice and of the first and second layers below it were 1,370 meters, 300 meters, and 720 meters respectively. Geologically the authors believe that the 5,000 m/sec layer represents a zone near the base of the ice cap where boulders of bed rock and moraine are frozen in the ice. The 5,450 m/sec layer is typical of the metamorphic basement. The upper refraction horizons show little west dip and one can assume that the 6,650 m/sec velocity is not far from the true value. If this be true, then a layer of basic rock, probably basalt, exists within the metamorphic basement. Near the coasts, basalt occurs rather commonly.

PAUL WUENSCHEL

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DISCUSSIONS AND COMMUNICATIONS

PROPAGATION OF TRANSIENT ELECTROMAGNETIC WAVES IN A CONDUCTING MEDIUM

Wait (1951) has calculated the transient electric fields for several types of step-function current sources placed inside a conducting medium. Now any generated pulse will require a finite build-up time to reach its final magnitude from its initial value of zero. In most cases, this type of pulse may be very well approximated by a ramp-function pulse (Figure 1). Expressions for the electric field of this type of pulse will be deduced in the following analysis.

Let us assume that an electric dipole is immersed in a homogeneous, isotropic medium having conductivity σ, dielectric constant ϵ, and permeability μ. If displacement currents be neglected in

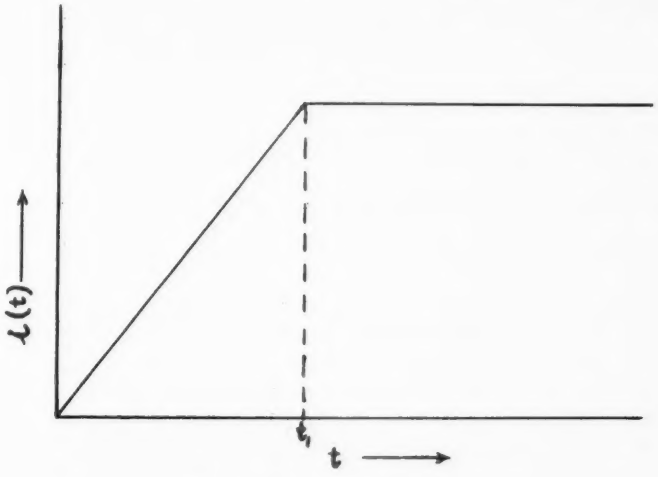

FIG. 1. Plot of ramp function.

comparison with conduction currents, we may write the expressions for the non-vanishing field components in spherical coordinates as follows (Wait, 1951):

$$e_r(s) = \frac{i(s)ds}{2\pi\sigma r^3}(1 + \alpha s^{1/2})e^{-\alpha s^{1/2}} \cos\theta \tag{1}$$

$$e_\theta(s) = \frac{i(s)ds}{4\pi\sigma r^3}(1 + \alpha s^{1/2} + \alpha^2 s)e^{-\alpha s^{1/2}} \sin\theta \tag{2}$$

and

$$h_\phi(s) = \frac{i(s)ds}{4\pi r^2}(1 + \alpha s^{1/2})e^{-\alpha s^{1/2}} \sin\theta \tag{3}$$

where

$$\alpha^2 = \sigma\mu r^2$$

and $i(s)$, $e_r(s)$, $e_\theta(s)$, and $h_\phi(s)$ are the Laplace transforms of $i(t)$, $e_r(t)$, $e_\theta(t)$, and $h_\phi(t)$.

The Laplace transform of a function representing a ramp-function current pulse $i(t)$ which begins at time $t=0$ and flattens out at time $t=t_1$ (Figure 1), is given by

$$i(s) = \frac{I}{t_1}\cdot\frac{1}{s^2}\left[1 - e^{-st_1}\right]. \tag{4}$$

Substituting (4) into (1) and normalizing by the substitutions

$$t \equiv \frac{t}{\alpha^2}, \quad e_r(s) \equiv \frac{e_r(s) \cdot 2\pi\sigma r^3}{Ids \cos\theta}, \quad \text{and} \quad t_r \equiv \frac{t_1}{\alpha^2},$$

we obtain

$$e_r(s) = \frac{1}{t_r} \cdot \frac{(1 + s^{1/2})e^{-s^{1/2}}}{s^2} \cdot [1 - e^{-st_r}]. \tag{5}$$

The inverse Laplace transform of (5) may be obtained by utilizing the following two important results:

$$L^{-1}\left(\frac{e^{-s^{1/2}}}{s^{3/2}}\right) = \frac{2}{\sqrt{\pi}} t^{1/2} - 1 + \frac{2}{\sqrt{\pi}} \cdot \left(\frac{1}{2\sqrt{t}}\right)\left[\frac{1}{2} - \frac{1}{3\cdot 4}\left(\frac{1}{2\sqrt{t}}\right)^2 + \frac{1}{2!}\cdot\frac{1}{5\cdot 6}\left(\frac{1}{2\sqrt{t}}\right)^4 - \frac{1}{3!}\cdot\frac{1}{7\cdot 8}\left(\frac{1}{2\sqrt{t}}\right)^6 + \cdots\right] \tag{6}$$

and

$$L^{-1}\left(\frac{e^{-s^{1/2}}}{s^2}\right) = t - \frac{2}{\sqrt{\pi}} t^{1/2} + \frac{1}{2} - \frac{2}{\sqrt{\pi}}\left(\frac{1}{2\sqrt{t}}\right) \cdot \left[\frac{1}{2\cdot 3} - \frac{1}{3\cdot 4\cdot 5}\left(\frac{1}{2\sqrt{t}}\right)^2 + \cdots\right] \tag{7}$$

where L^{-1} denotes the inverse Laplace transform.

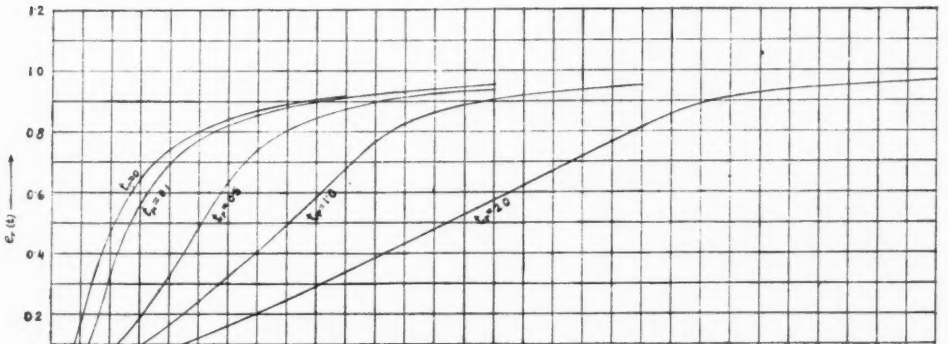

FIG. 2. Radial electric field component as function of time for various build-up times.

With the help of equations (6) and (7), equation (5) may be expressed in the following way, after some algebraic manipulations, for the two separate time-domains:

(i) $0 \leqq t \leqq t_r$

$$E_r(t) = \frac{1}{t_r} \cdot f_1(t) \tag{8}$$

and (ii) $t \geqq t_r$

$$E_r(t) = \frac{1}{t_r}[f_1(t)u(t) - f_1(t - t_r)u(t - t_r)], \tag{9}$$

where $u(t)$ and $u(t-t_r)$ are step-functions beginning at times $t=0$ and $t=t_r$ respectively and

$$f_1(t) = \left(t - \frac{1}{2}\right) + \frac{1}{4}\left[(2 - 4t)\ \text{erf}\left(\frac{1}{2\sqrt{t}}\right) + 2t^{1/2}\ \text{erf}'\left(\frac{1}{2\sqrt{t}}\right)\right]. \tag{10}$$

A plot of $E_r(t/\sigma\mu r^2)$ against $t/\sigma\mu r^2$ is given in Figure 2 for five different values of t_r, (i) $t_r=0$ (a step-function input, Wait, 1951), (ii) $t_r=0.1$, (iii) $t_r=0.5$, (iv) $t_r=1.0$, and (v) $t_r=2.0$.

In a similar way, the following expressions for $E_\theta(t)$ and $H_\phi(t)$ may be obtained for two separate time intervals:

(i) $0 \leqq t \leqq t_r$

$$E_\theta(t) = \frac{1}{t_r} f_2(t) \tag{11}$$

and

$$H_\phi(t) = \frac{1}{t_r} f_1(t) \tag{12}$$

and (ii) $t \geqq t_r$

$$E_\theta(t) = \frac{1}{t_r}\left[f_2(t)u(t) - f_2(t-t_r)u(t-t_r)\right] \tag{13}$$

and

$$H_\phi(t) = \frac{1}{t_r}\left[f_1(t)u(t) - f_1(t-t_r)u(t-t_r)\right] \tag{14}$$

where

$$f_2(t) = \left(t - \frac{1}{2}\right) + \frac{1}{4}\left\{(2-4t)\operatorname{erf}\left(\frac{1}{2t^{1/2}}\right) + 2t^{1/2}\operatorname{erf}'\left(\frac{1}{2t^{1/2}}\right)\right\} + 1 - \operatorname{erf}\left(\frac{1}{2t^{1/2}}\right). \tag{15}$$

From a study of these functions it is observed that in the case of a ramp-function input pulse fed into a conducting medium, the non-vanishing components of the electric and magnetic field intensities exhibit time-gradients varying with the change in steepness of the exciting pulse-fronts. The magnitudes of the overshoots in the case of $E_\theta(t)$ begin to decrease as the ramp-function pulse takes a longer time to flatten off.

A study of the electric field intensities in the case of a saw-tooth pulse input has also been made in this laboratory. In geophysical exploration, saw-tooth pulses having large values of t_r should be used if one wishes to obtain an appreciable magnitude for the electric and magnetic field intensities. A sharp rise time for this sort of exciting pulse cannot give rise to field intensities which can be easily measured. A detailed paper in this subject will be shortly published in the *Journal of Science and Engineering* of the Indian Institute of Technology, Kharagpur.

The author is grateful to Prof. P. K. Bhattacharyya for his valuable suggestions and advice during the progress of the work.

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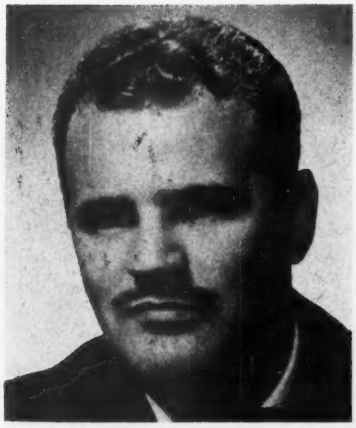

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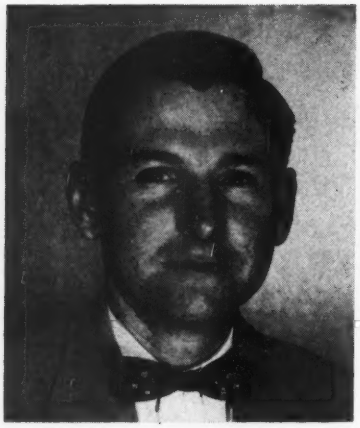

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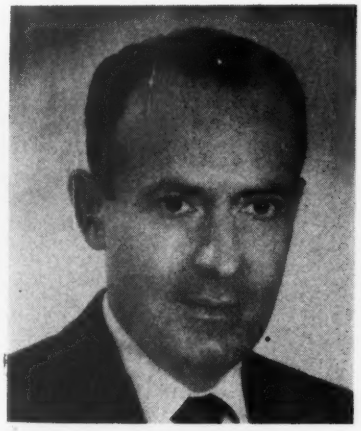

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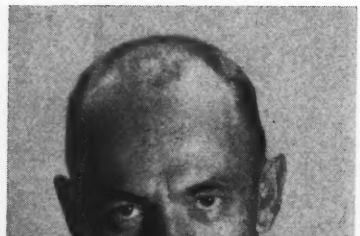

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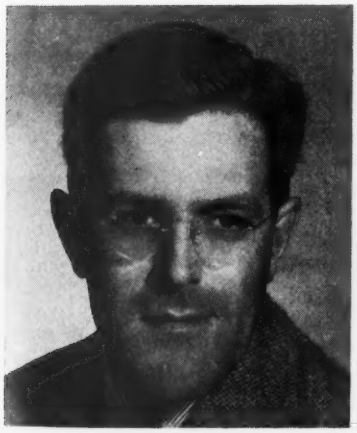

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Biographies and photographs of the following authors may be found in recent issues of GEOPHYSICS: W. B. AGOCS, v. XIX, p. 351 (April, 1954); J. F. ENSLIN, v. XX, p. 353 (April, 1955); NEAL J. JONES, v. XIX, p. 845 (October, 1954); JOHN A. MORRISON, v. XIX, p. 847 (October, 1954); ALLEN F. RUMMERFIELD, v. XIX, p. 847 (October, 1954); and BART W. SORGE, v. XX, p. 395 (April, 1955).

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LOCAL SECTIONS

GEOPHYSICAL SOCIETY OF TULSA

(CHARTERED FEBRUARY 2, 1948)

President: JOHN M. CRAWFORD, Continental Oil Co., Ponca City, Okla.
1st Vice-President: STANLEY WILCOX, Seismograph Service Corp., Box 1590, Tulsa 1, Okla.
2nd Vice-President: WILLIAM M. ERDAHL, Skelly Oil Co., Box 1650, Tulsa, Okla.
Secretary: JOHN RUPNIK, Manhart, Millison & Beebe, Jenkins Bldg., Tulsa, Okla.
Treasurer: R. B. RICE, Phillips Petroleum Co., Bartlesville, Okla.
Editor: E. V. MCCOLLUM, E. V. McCollum & Co., 515 Thompson Bldg., Tulsa, Okla.
District Representatives:
NORMAN RICKER, The Carter Oil Co., Box 801, Tulsa, Okla.
L. Y. FAUST, Amerada Petroleum Corp., Box 2240, Tulsa, Okla.
PAUL L. LYONS, Sinclair Oil & Gas Co., Box 521, Tulsa, Okla.
Meetings: Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, Room 224, Petroleum Science Hall.

SOCIETY OF EXPLORATION GEOPHYSICISTS HOUSTON SECTION

(CHARTERED FEBRUARY 14, 1948)

President: T. O. HALL, General Geophysical Co., 2514 Gulf Bldg., Houston 2, Texas
1st Vice-President: FRED E. ROMBERG, Geophysical Service Inc., 839 Esperson Bldg., Houston 2, Texas
2nd Vice-President: A. A. HUNZICKER, Seismic Explorations, Inc., 1007 S. Shepherd, Houston, Texas

Secretary: H. W. McDONNOLD, Keystone Exploration Co., 2813 Westheimer, Houston, Texas
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District Representatives:
O. B. HOCKER, The Texas Co., Box 2332, Houston 1, Texas
G. A. BERG, Berg Geophysical Co., 2122 Welch, Houston, Texas
JOHN F. ANDERSON, Anderson & Cooke, 500 San Jacinto Bldg., Houston, Texas
Meetings: Monthly, 1st Monday, Noon luncheon ($1.50), Rice Hotel.

PACIFIC COAST SECTION

(CHARTERED APRIL 12, 1948)

President: JOHN W. MATHEWS, Richfield Oil Co., Box 147, Bakersfield, Calif.
Vice-President Northern District: RICHARD W. SHOEMAKER, Ohio Oil Co., Box 193, Bakersfield, Calif.
Vice-President Southern District: ELLSWORTH M. CURRY, Shell Oil Co., 1008 W. 6th St., Los Angeles 17, Calif.
Secretary-Treasurer: I. V. SCHERB, The Texas Co., Box 3127, "H" St. Annex, Bakersfield, California
District Representatives:
FLINT H. AGEE, United Geophysical Corp., 2227 S. 4th Ave., Arcadia, Calif.
WM. D. CORTRIGHT, Tide Water Associated Oil Co., 2202 Terrace Way, Bakersfield, Calif.
MILTON C. BORN, Amerada Petroleum Corp., 552 Subway Terminal Bldg., Los Angeles, Calif.
Meetings: Monthly, 2nd Thursday, Noon luncheon ($2.00), Biltmore Hotel, Los Angeles.

DALLAS GEOPHYSICAL SOCIETY

(CHARTERED AUGUST 7, 1948)

President: R. C. DUNLAP, JR., Geophysical Service Inc., 5900 Lemmon Ave., Dallas 9, Texas
1st Vice-President: MARTIN C. KELSEY, Rayflex Exploration Co., 6923 Snider Plaza, Dallas, Texas
2nd Vice-President: TOM PRICKETT, The Atlantic Refining Co., Box 2819, Dallas 1, Texas
Secretary-Treasurer: JOHN T. GEER, Magnolia Petroleum Co., Box 900, Dallas 1, Texas
District Representatives:
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CECIL H. GREEN, Geophysical Service Inc., 5900 Lemmon Ave., Dallas 9, Texas
J. P. WOODS, The Atlantic Refining Co., Box 2819, Dallas 1, Texas
Meetings: Monthly, generally but not invariably 2nd Monday (contact any member). 8:00 P.M. Fondren Science Bldg., S.M.U.

FORT WORTH GEOPHYSICAL SOCIETY

(CHARTERED AUGUST 7, 1948)

President: E. J. GEMMILL, Cities Service Oil Co., 1111 Ft. Worth National Bank Bldg., Fort Worth, Texas
Vice-President: H. E. PROKESH, Continental Oil Co., 1710 Fair Bldg., Fort Worth, Texas
Secretary-Treasurer: JAMES DIVELBISS, The Chicago Corp., 2122 Continental Life Bldg., Fort Worth, Texas
District Representatives:
F. O. MORTLOCK, Gulf Research & Development Co., Drawer 1290, Fort Worth, Texas
L. O. SEAMAN, Sinclair Oil & Gas Company, 901 Fair Bldg., Fort Worth, Texas
Meetings: Monthly, 4th Monday, Noon Luncheon ($1.50), Texas Hotel.

ARK-LA-TEX GEOPHYSICAL SOCIETY

(CHARTERED MARCH 12, 1949)

President: J. RYAN WALKER, Arkansas Fuel Oil Corp., Box 1171, Shreveport, La.
Vice-President: GLENN J. BAKER, Wm. M. Barret, Inc., 1431 Dalzell, Shreveport, La.

Secretary-Treasurer: BRUCE FOX, The Atlantic Refining Co., 922 Texas Eastern Bldg., Shreveport, La.
District Representatives:
B. B. BURROUGHS, Sunray Oil Corp., Ricou-Brewster Bldg., Shreveport, La.
ROBERT B. BAUM, Seismograph Service Corp., Box 1590, Tulsa 1, Oklahoma.
Meetings: Monthly, last Monday, Noon Luncheon ($1.50), Caddo Hotel, Shreveport.

PERMIAN BASIN GEOPHYSICAL SOCIETY

(CHARTERED JANUARY 30, 1950)

President: J. E. FINLEY, Continental Oil Co., Box 431, Midland, Texas
1st Vice-President: J. S. PLUTA, Honolulu Oil Corp., Drewer 1391, Midland, Texas
2nd Vice-President: R. M. PINSON, Union Oil Co., 619 West Texas, Midland, Texas
Secretary: BILLY C. JOHNSON, Forest Oil Corp., Box 2066, Midland, Texas
Treasurer: N. R. PARK, Standard Oil Co. of Texas, McClintic Bldg., Midland, Texas
District Representative: PAUL C. REED, Forest Oil Corp., Box 2066, Midland, Texas
Meetings: Monthly, 2nd Tuesday, 7:30 P.M., free coffee and doughnuts, Cowden Jr. High School cafeteria.

DENVER GEOPHYSICAL SOCIETY

(CHARTERED MAY 19, 1950)

President: C. K. SHEPHERD, Continental Oil Co., Continental Oil Bldg., Denver, Colorado
Vice-President: E. B. WASSON, The California Co., Box 780, Denver, Colorado
Secretary-Treasurer: J. R. REEVES, Aurora Gasoline Co., 227 U. S. National Bank Bldg., Denver, Colorado
District Representative: DART WANTLAND, 727 Pearl St., Denver, Colorado
Meetings: Monthly, 1st Monday, 5:30 P.M., meeting only, Petroleum Club, 1644 Glenarm Place.

CANADIAN SOCIETY OF EXPLORATION GEOPHYSICSTS

(CHARTERED JANUARY 24, 1952)

President: R. D. HOLLAND, Texaco Exploration Co., 237 7th Ave., Calgary, Alberta
Vice-President: E. G. HAINES, Seaboard Oil Co., 630 8th Ave., W., Calgary, Alberta
Secretary-Treasurer: H. J. MCGREW, Canadian Gulf Oil Co., Box 130, Calgary, Alberta
District Representative: F. G. COOTE, Accurate Exploration Ltd., 2201 10th Ave., W., Calgary, Alberta
Meetings: (Data not received)

GEOPHYSICAL SOCIETY OF OKLAHOMA CITY

(CHARTERED SEPTEMBER 30, 1952)

President: J. E. STONES, The Superior Oil Co., 2211 Liberty Bank Bldg., Oklahoma City, Okla.
1st Vice-President: R. D. ROBERTS, Sohio Petroleum Co., Box 3656, Oklahoma City, Okla.
2nd Vice-President: D. J. VAN NOSTRAND, Gulf Oil Corp., Box 9667, Oklahoma City, Okla.
Secretary: JOHN BEMROSE, Sohio Petroleum Co., Box 3656, Oklahoma City, Okla.
Treasurer: R. H. PEACOCK, Superior Oil Co., 2211 Liberty Bank Bldg., Oklahoma City, Okla.
District Representative: D. W. RATLIFF, Stanolind Oil & Gas Co., Box 1654, Oklahoma City, Okla.
Meetings: Monthly, 2nd or 3rd Monday, time and place to be announced.

CASPER GEOPHYSICAL SOCIETY

(CHARTERED MAY 23, 1953)

President: G. NEWMAN SHELL, Cities Service Oil Co., 1719 S. Oak, Casper, Wyo.
Vice-President: GEORGE N. MEADE, Stanolind Oil & Gas Co., Box 40, Casper, Wyo.
Secretary-Treasurer: WESLEY N. FARMER, Richfield Oil Corp., Box 698, Casper, Wyo.

District Representative: HOMER ROBERTS, Petty Geophysical Engineering Co., Box 651, Casper, Wyoming
Meetings: Monthly, 1st Monday, 7:00 P.M., Dinner ($2.75), Townsend Hotel

GEOPHYSICAL SOCIETY OF SOUTH TEXAS

(CHARTERED NOVEMBER 9, 1953)

President: WELDON L. CRAWFORD, Petty Geophysical Engineering Co., Transit Tower, San Antonio Texas
Vice-President: LEE MOORE, Petty Geophysical Engineering Co., Transit Tower, San Antonio, Texas
Secretary-Treasurer: LAWTON B. STEPHENSON, Petty Geophysical Engineering Co., Transit Tower, San Antonio, Texas
District Representative: BART PRATT, Petty Geophysical Engineering Co., Box 2061, San Antonio, Texas
Meetings: Semi-monthly, 2nd and 4th Wednesdays, Noon luncheon (Cafeteria style), Sommers Cafeteria, Main Plaza, San Antonio.

SOUTHEASTERN GEOPHYSICAL SOCIETY

(CHARTERED APRIL 1, 1954)

President: G. A. BURTON, Shell Oil Co., Box 193, New Orleans, La.
Vice-President: J. A. HARRIS, The California Co., 800 The California Co., Bldg., New Orleans 12, La
Secretary-Treasurer: J. B. MEITZEN, Humble Oil & Refg. Co., Box 626, New Orleans 7, La.
District Representatives:
CLARK E. ALLEN, Geophysical Service Inc., 522 Arlington Dr., New Orleans 20, La.
K. R. WELLS, General Geophysical Co., 5025 St. Bernard Ave., New Orleans, La.
Meetings: Monthly, 3rd Monday, Noon luncheon ($1.50), St. Charles Hotel, New Orleans.

MONTANA GEOPHYSICAL SOCIETY

(CHARTERED APRIL 12, 1954)

President: D. M. STEEL, Geotechnical Corp., 251 Avenue F, Billings, Montana
1st Vice-President: H. R. ADAMS, Sohio Petroleum Co., Box 529, Billings, Montana
2nd Vice-President: EDWIN BARTEL, Petty Geophysical Engrg. Co., 403 North 24th St., Billings, Montana
Secretary-Treasurer: S. G. BUFORD, JR.
Meetings: (Data not received)

DAKOTA GEOPHYSICAL SOCIETY

President: W. E. PHILLIPS, Stanolind Oil & Gas Co., Box 1437, Bismarck, N. D.
1st Vice-President: HUGH MCCAIN, The Atlantic Refining Co., Box 1076, Bismarck, N. D.
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Secretary-Treasurer: R. R. PHAIR, Roundup Powder Co., Box 452, Bismarck, N. D.
District Representative: HENRY NOGAMI, The Atlantic Refining Co., Box 728, Dickinson, North Dakota
Meetings: Monthly, 1st Friday, 7:30 P.M., Petroleum Club, Prince Hotel, Bismarck.

JACKSON GEOPHYSICAL SOCIETY

(CHARTERED MAY 12, 1955)

President: FRED G. KNIGHT, The Ohio Oil Co., Box 850, Lafayette, Louisiana
Vice-President: PHIL P. GABY, Delta Exploration Co., 206 West Rankin St., Jackson, Mississippi

Secretary-Treasurer: ROBERT R. PHILLIPS, Honolulu Oil Corp., 403 Deposit Guaranty Bank Bldg., Jackson, Mississippi
District Representative: To be elected
Meetings: To be announced.

STUDENT SOCIETIES

(AFFILIATED)

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President: WILLIAM F. CLARKE
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Faculty Sponsor: JOHN C. HOLLISTER
Meetings: (Data not received)

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Treasurer: ROBERT RILEY
Faculty Moderator: REV. JAMES B. MACELWANE, S.J., Institute of Technology, 3621 Olive St., St. Louis 8, Mo.
Meetings: Monthly, 2nd Wednesday, 7:30 P.M., Meeting only, Institute of Technology, 3621 Olive Street.

SOCIETY OF EXPLORATION GEOPHYSICISTS HOUSTON STUDENT SECTION

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University of Houston Sponsor: R. A. GEYER, 3743 Childress St., Houston 1, Texas
Rice Institute Sponsor: C. R. WISCHMEYER, The Rice Institute, Houston, Texas
Meetings: (Data not received)

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Secretary-Treasurer: R. M. FARQUHAR
Faculty Sponsor: J. TUZO WILSON
Meetings: Bi-weekly, alternate Thursdays, 4:00 P.M., 49 St. George St.

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President: JACK NOBLE
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Treasurer: SCOTT SMITH
Meetings: Every Tuesday, 7:00 P.M., meeting only, Petroleum Science Hall.

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Faculty Sponsor: WM. S. STRAIN
Meetings: To be announced.

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Secretary: ALFRED E. WILLIAMS *Faculty Sponsor:* B. F. HOWELL, JR.

CALENDAR OF MEETINGS

October 3–6, 1955: 25th Annual Meeting SEG, Shirley Savoy Hotel, Denver, Colorado
March 8–9, 1956: Midwestern Regional Meeting, Texas Hotel, Fort Worth, Texas
May 11, 1956: Annual Spring Meeting, Pacific Coast Section, SEG, El Tejon Hotel, Bakersfield, California
May 12, 1956: Annual Meeting, Permian Basin Geophysical Society, Scharbauer Hotel, Midland, Texas
May 17–18, 1956: Gulf Coast Regional Meeting, Houston, Texas
October 29–31; Nov. 1, 1956: 26th Annual Meeting SEG, Roosevelt Hotel, New Orleans, La.
November 11–14, 1957: 27th Annual Meeting SEG, the Statler-Hilton, Dallas, Texas.

MEMBERSHIP APPLICATIONS RECEIVED

Applications for Active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. If any member has information bearing on the qualifications of these candidates he should send it to the President within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

ALEXANDER, ROGER G., JR., *Geologist-Geophysicist*, Standard Oil Co. of California, P.O. Box 278, Oildale, Calif.

ANDERSON, WALLACE L., *Research Engineer*, McCollum Exploration Co., 1025 S. Shepherd Dr., Houston, Texas

ATCHISON, CARL H., *Mgr. of Exploration*, British American Oil Prod. Co., 806 V & J Tower, Midland, Texas

BASURTO, JESUS G., *Ass't To Chief Geophysicist*, Petroleos Mexicanos, Esparza Oteo 175, Mexico 20, D.F. Mexico

BILY, ROY J., *Field Supervisor*, Imperial Oil Ltd., 8536-109 Street, Edmonton, Alta., Canda

BLEVINS, HOWARD M., *Supervisor*, Tomlinson Geophysical Service, 524 Commercial Bldg., Shreveport, La.

BOYDSTUN, JAMES A., *Computer*, Union Producing Co., P.O. Box 1407, Shreveport, La.

BREMKAMP, WILLIAM, *Party Chief*, Continental Geophysical Co., 602 Continental Life Bldg., Ft. Worth, Texas

BRUBAKER, D. G., *Research Physicist*, The New Jersey Zinc Co., Research Dept., Palmerton, Pa.

CARLSON, HARRY W., *Review Geophysicist*, The California Co., P.O. Box 780, Denver, Colo.

CARR, ROBERT B., *Sr. Geophysicist*, c/o Arabian American Oil Co., Dhahran, Saudi Arabia

CARTER, WILLIAM H., JR., *President*, Electro Mechanical Development, 2337 Bissonnet Ave., Houston 5, Texas

CLARK, JOHN E., *Geophysicist*, Union Oil Co. of California, 619 W. Texas, Midland, Texas

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DUMAS, W. B., *Seismic Supervisor*, Kerr-McGee Oil Ind. Inc., 3420 NW 23rd Street, Oklahoma City, Okla.

DYAR, ROBERT F., *Geophysicist*, Gulf Oil Corp., P.O. Drawer 2100, Houston 1, Texas

FENDLASON, L. J., *Area Gravity Supervisor*, Shell Oil Co., Box 193, New Orleans 3, La.

FERRELL, L. M., *Field Supervisor*, Delta Exploration Co., 206 Rankin St., Jackson, Miss.

FISHER, BILL M., *Party Manager*, United Geophysical Corp., Box 478, Miles City, Mont.

FOGARTY, CHARLES F., *Mgr. Geological Dept.*, Texas Gulf Sulphur Co., Rm. 1804, 811 Rusk Ave., Houston 2, Texas

Gray, C. H., Jr., *Party Chief*, Gravity Meter Exploration Co., P.O. Box 907, Morgan City, La.

teGroeh, Dick M. W. *Geophysicist*, Ned Nieuw Guinee Petr. Naatshappy, Sorong Ned. Nw. Guinea

Hallock, C. E., Jr., *Geophysical Supervisor*, Phillips Petroleum Co., 341 SE. Waverly, Bartlesville, Okla.

Hambleton, William W. *Ass't. Prof. Geology*, University of Kansas, Dept. of Geology, Lawrence, Kan.

Herrmann, Arthur C., Jr., *Sr. Observer*, The Atlantic Refining Co., P.O. Box 2819, Dallas, Texas

Hoffschwelle, John W. *Party Chief*, Gulf Oil Corp., Box 1815, Billings, Mont.

Holtzcherer, J. J. *Geophysicist*, Esso-Rep, France, 2 Cours Victor Hugo, Belges, (Girande), France

Huckabay, W. B. *Sr. Research Technologist*, Magnolia Petroleum Co., P.O. Box 900, Dallas, Texas

Khan, Riaz H. *Geophysicist*, Offshore Exploration Group H., 3601 S. Sandman, Houston, Texas

Kimball, W. C. *Supervisor*, Apache Exploration Co., Inc., P.O. Box 1711, Houston 1, Texas

Knittle, R. B. *Party Chief*, The Texas Co., P.O. Box 1012, Houma, La.

Lopes, Eudes P. *Geop'rysicist*, Petrobas, 2212 Ford St., Apt. 1, Golden, Colo.

Martin, Jack P. *Geologist*, Texas Gulf Producing Co., 413 Marguerite Blvd., Lafayette, La.

Mayne, W. Harry, *Research Engineer*, Petty Laboratories, Inc., Box 2061, San Antonio, Texas

McDonald, J. Kenneth, *Party Chief*, Oklahoma Seismograph Co., P.O. Box 579, Shawnee, Okla.

Muir, David M., *Manager*, Radio Geophysical Co., 5209 N. Lamar Boulevard, Austin 5, Texas

Murray, Joseph E., *Geophysicist*, Stanolind Oil & Gas Co., P.O. Box 1654, Oklahoma City, Okla.

Piggott, H. D. G., *Geophysicist*, British Petroleum Co., Ltd., 52, Claygate Lane, Hinchley Wood, Esher, Surrey, England

Prins, S., *Seismologist*, c/o Compania Shell de Venezuela, Ltd., Apartado 19, Maracaibo, Venezuela

Robinson, Robert E., *Chief Petro. Eng. & Geol.*, Trans-American Petroleum Corp., 1839 Line Avenue, Shreveport, La.

Schisler, Alvin J., *Party Chief*, Exploration Consultants, Inc., 503 Jenkins Bldg., Tulsa, Okla.

Schwartz, Bob A., *Party Chief*, Exploration Consultants, Inc., 209A-6th Avenue W., Calgary Alta., Canada

Sheldon, John A., *Zone Geophysicist*, Gulf Oil Corp., P.O. Box 669, Roswell, N. M.

Sims, Elmer R., Jr., *Instrument Supervisor*, Empire Geophysical, Inc., Box 561, Odessa, Texas

Smith, Louis M., *Geophysicist*, Sun Oil Company, P.O. Box 2831, Beaumont, Texas

Van Altena, Peter J., *Area Manager*, Cardinal Geophysical Co., Inc., 533 Petroleum Bldg., Wichita, Kan.

Walker, E. R., *Staff Engineer*, Midwestern Instruments, P.O. Box 7186, Tulsa, Okla.

Walthall, Max H., *Seismic Computer*, Humble Oil and Ref. Company, P.O. Box 626, New Orleans, La.

Westmacott, Robert I., *Party Geophysicist*, Stanolind Oil & Gas Co., P.O. Box #509, Denver, Colo.

Yeager, J. C., *Seismic Party Chief*, The Texas Co., P.O. Box 1720, Ft. Worth, Texas

TRANSFER TO ACTIVE MEMBERSHIP

Campbell, Edmund O., *Geophysicist*, Gulf Oil Corp., P.O. Drawer 2100, Houston, Texas

Dayton, Morris E., *Ass't Geophysicist & Geologist*, Texas Pacific Coal & Oil Co., P.O. Box 155, Abilene, Texas

Drake, Marvin E., *Seismologist*, Rogers Exploration, S. A., Apartado 463, Caracas, Venezuela

Ekstrom, James J., *Party Chief*, United Geophysical Corp., Bin "M", Pasadena, Calif.

Haseltine, Harvey M., Jr., *Party Chief*, The Atlantic Refining Co., 3629 Shenandoah, Dallas 5, Texas

Hope, Ray, *Party Chief*, General Geophysical Co., 705 Houston Club Bldg., Houston, Texas

HUGHES, JAMES R., *Party Chief*, Geophysical Service Inc., 5900 Lemmon Ave., Dallas 9, Texas

MCCAMUS, F. W., *Geophysicist*, McPhar Geophysics Ltd., 36 Cranfield Rd., Toronto 16, Ont., Canada

NEITZEL, EDWIN B., *Electrical Engineer*, The Atlantic Refining Co., Geophysical Lab., P.O. Box 2819, Dallas 1, Texas

NEWMAN, C. E., *Geophysicist*, Gulf Oil Corp., P.O. Box 478, Monahans, Texas

NOREM, N. M., *Party Chief*, Geophysical Service Inc., Caixa Postal No. 820, Belem, Para, Brasil

PARKER, KENNETH L., *Geophysicist*, Research Exploration Inc., 5406 Grand Lake St., Bellaire, Texas

PERCY, C. G., *Seismic Computer*, Humble Oil & Refining Co., Box 1600, Midland, Texas

SLAVEN, THOMAS LANE, *Staff Geophysicist*, Western Geophysical Co. of America, 813 S. Bonnie Brae St., Los Angeles 57, Calif.

TAMAGE, E. W., *Geophysicist*, Sinclair Oil & Gas Co., P.O. Box 99, Jackson, Mississippi

THOMAS, GEORGE L., *Computer*, Geophysical Service Inc., 6424 Pipeline Rd., Ft. Worth, Texas

THOMPSON, JACK H., *Party Chief*, Sun Oil Co., Seismograph Dept., Box 1798, Denver, Colo.

WARD, CHARLES J., *Geophysicist*, Seaboard Oil Company, 8518 Ridgelea St., Dallas 9, Texas

WOKER, LEONARD A., *Party Chief*, The Texas Co., General Delivery, Claresholm, Alt., Canada

AWARD FOR BEST PAPER OF 1954

Ben F. Rummerfield (left) received the certificate and plaque representing the annual Best Paper Award for 1954 from President Paul L. Lyons during the opening session of the Annual Joint Meeting March 29, 1955 in New York City. Mr. Rummerfield's paper, "Reflection Quality, a Fourth Dimension," appeared in the October, 1954 issue of GEOPHYSICS.

ANNOUNCEMENTS

NINTH ANNUAL MIDWESTERN MEETING

Plans are well under way for the Ninth Annual Midwestern Meeting of SEG to be held in the Texas Hotel, Fort Worth, March 8 and 9, 1956. General Chairman E. L. Mount, of the Continental Oil Co., Oklahoma City, has announced that members who desire to present papers at this meeting may contact R. M. Davis, Program Chairman, care of The Carter Oil Co., 1411 Classen Blvd., Oklahoma City, Oklahoma. The Geophysical Society of Oklahoma City is the principal sponsor, with the Fort Worth Geophysical Society serving as host. The other four local sections sponsoring the meeting are the Ark-La-Tex Geophysical Society (Shreveport), Dallas Geophysical Society, Geophysical Society of Tulsa, and Permian Basin Geophysical Society (Midland).

To date the following committeemen have been appointed: R. M. Davis and F. A. Roberts, Co-chairmen of the Program Committee from Oklahoma City, and L. V. Lombardi, member from Fort Worth; G. V. Dunn and Marvin Hewitt, Co-chairmen from Oklahoma City of the Finance Committee, and A. F. Pankey, Fort Worth member; R. D. Roberts and H. C. Talley, Jr., Oklahoma City Co-chairmen of the Program Publicity Committee, and Ben F. Rummerfield, Tulsa member; Kirby Warren, Fort Worth Chairman of the Entertainment Committee, and Ed A. Deupree, Oklahoma City Co-chairman; B. J. Boring, Fort Worth Chairman of the Publicity Committee, and L. D. Ervin, Oklahoma City Co-chairman; G. A. Bell, Jr., Fort Worth Chairman of the Registration Committee, and John R. Foster, Oklahoma City Co-chairman; A. E. McKay, Fort Worth Chairman of the Housing Committee, and John M. Cochrane, Oklahoma City Co-chairman; and James Divelbiss, Fort Worth Chairman of the Arrangements Committee, and W. H. Speckhard, Oklahoma City Co-chairman.

GEOPHYSICIST RECEIVES NAVY'S HIGHEST CIVILIAN AWARD

Dr. Maurice Ewing, director of the Lamont Geological Observatory, Palisades, New York, and a pioneer scientist in underwater sound research, has received the Navy's Distinguished Public Service Award for his outstanding contributions to the science of undersea warfare.

The citation accompanying the award reads in part:

"For his outstanding contributions to the United States Navy in the scientific development of undersea warfare. His vigorous pursuit of general understanding of marine phenomena has placed him at the forefront of the fields of oceanographic geophysics and underwater acoustics. His contributions to the National Defense may be measured by the fact that the Navy's ability to detect submarines acoustically rests to a large extent on his early work on the propagation of sound in the ocean. . . . Of equal importance in the defense of the United States have been his contributions as a leader and teacher. His success may be judged by the fact that many of the outstanding men today in the fields of underwater sound, oceanography, and geophysics have at one time been his students. . . . "

In announcing this award, the Navy released the following statement:

"The award was presented for Dr. Ewing's contributions in marine geophysics. He has been a prolific pioneer and producer in the oceanographic-acoustic research aspects of underwater sound; his basic research has contributed to the Navy's increased capabilities in antisubmarine warfare; and his work has led to new equipments and operational concepts in this important Navy field.

"Dr. Ewing also has been a guiding spirit in submarine geophysics, sound transmission, and certain aspects of submarine warfare for 10 to 20 years. Because of his work in underwater sound he became the principal developer of the techniques now used by many people in this field. In addition, he interested many students in oceanic research and trained many of the present scientific leaders in this field.

"He pioneered investigations in seismic refraction measurements, underwater photography, precision sounding, bottom sediment coring, gravity measurements and their theoretical interpretation, and the erosion and sedimentation properties of turbidity currents. His work contributed immeasur-

ably to development of the bathythermograph and use of the deep sound channel for position finding at sea.

"He was awarded the Day Medal in 1949 by the Geological Society of America. Dr. Ewing is a member of the National Academy of Sciences and this year was awarded the Agassiz Medal for his outstanding contributions in marine geophysics and geology. He is a fellow of the Physical Society, the Geological Society, and the Mathematical Society. He has been vice-president of the Geophysical Union and the Seismological Society.

PERSONAL ITEMS

DR. JOSEPH W. BERG, JR. has accepted the position of Assistant Professor in the Department of Geophysics, University of Utah, Salt Lake City, Utah. Dr. Berg was formerly Assistant Professor of Geophysics at The University of Tulsa.

DR. KENNETH L. COOK has been promoted to the rank of full Professor and Head of the Department of Geophysics, University of Utah.

PHILIP M. KONKEL has been appointed assistant chief geologist for The Ohio Oil Co. effective July 1, 1955, according to an announcement by Fred E. Smith, vice-president and manager of the production department.

JO PAT BLACK, former assistant to the president of the American Republic Corp., has opened his own geology and geophysical consulting business with offices in the San Jacinto Building, Houston, Texas.

CHARLES H. DRESBACH, for the past five years Manager of Societe Nord Africaine des Petroles (SNAP), Gulf Oil subsidiary in Tunisia, North Africa, is now located at Accra, Gold Coast, as Representative—West Africa—Gulf Eastern Co. (Gulf Oil).

The appointment of JULIAN C. ASHBY to be General Manager of Utex Exploration Company, Inc., has been announced by Charles A. Steen, president of Utex, Moab, Utah.

COL. MERLE C. BOWSKY is now stationed at Ft. Huachuca, Arizona.

K. STEWART CRONIN was appointed exploration manager of the Pure Oil Company effective July 1, it was announced by R. B. Kelly, vice president for exploration and production. Mr. Cronin, employed by the company in geological work for 21 years, succeeds DONALD M. DAVIS, who will become assistant manager of Pure's Gulf Coast producing division with headquarters in Houston.

MILLER QUARLES, JR. resigned his position as Chief Geophysicist and Gulf Coast Manager of Precision Exploration Company effective June 15, 1955. He has joined Ralph E. Fair, Inc. at 1111 Milam Building, San Antonio, Texas, as a geologist and geophysicist.

ROBERT M. DREYER has been appointed Chief Geologist of the Kaiser Aluminum and Chemical Corp., Oakland, California.

R. W. DUDLEY, formerly of Kerr-Dudley & Co., Ft. Worth, Texas, has moved to Oklahoma City and opened an oil exploration consulting office at 608 First National Building.

PAUL FARREN, formerly Vice-President of National Geophysical Company, resigned effective October 1, 1955, after more than eighteen years service with that company, to open a geophysical consulting office in Houston. The new Second National Bank Building in Houston has promised him a suite of offices at No. 1528 by the middle of February. Until then he will be at 742 W. 42, Houston 18, Texas. He intends to specialize in seismic interpretation, review, and supervision.

J. W. FISHBACK has been named district geophysicist for Stanolind Oil and Gas Company's Roswell, New Mexico, district. Fishback replaces C. J. LONG, who has been transferred as district geophysicist of the company's Midland, Texas, district.

GEORGE C. MCGHEE announces the opening of an office in the Republic National Bank Building, Dallas. He has organized the McGhee Production company, which will carry on geophysical evaluation and exploratory drilling. The company will concentrate its activities in southern Louisiana, but will be active in all of the principal oil producing areas.

Mr. McGhee plans to purchase producing oil and gas properties through the recently organized Petroleum Reserves Incorporated.

SOCIETY OF EXPLORATION GEOPHYSICISTS
CONSTITUTION AND BYLAWS

CONSTITUTION

(As amended to August 26, 1948)

Article I.	Name	Article X.	Meetings
Article II.	Object	Article XI.	Local Sections
Article III.	Membership	Article XII.	Districts
Article IV.	Code of Ethics	Article XIII.	Affiliated Societies
Article V.	Election, etc. of Members	Article XIV.	Committees
Article VI.	Officers	Article XV.	Business Manager
Article VII.	Duties of Officers	Article XVI.	Review by Members
Article VIII.	Council	Article XVII.	Bylaws
Article IX.	Executive Committee	Article XVIII.	Amendments to the Constitution

Article I. Name

Section 1. The Society shall be called the "Society of Exploration Geophysicists."

Article II. Object

Section 1. The objects of this Society shall be to promote the science of geophysics especially as it relates to exploration and research, to foster the common scientific interests of geophysicists, and to maintain a high professional standing among its members.

Article III. Membership

Section 1. The membership of this Society shall consist of persons elected and qualified in accordance with the Constitution and Bylaws of this Society at the time of such election.

Section 2. The membership of this Society shall consist of Honorary Members, Active Members, Associate Members, and Student Members.

Section 3. To be eligible to election to Honorary Membership a person shall, in the unanimous opinion of the Standing Committee on Honors and Awards and the Council, have made a distinguished contribution to geophysics or a related field which warrants exceptional recognition.

Section 4. To be eligible to election to Active Membership an applicant must have been actively engaged in practicing or teaching geophysics or a related field for not less than eight years (up to four years as a student in a recognized college or university may be counted toward this total) of which at least three years must have involved work of a responsible nature calling for independent judgment and the application of geophysical or geological principles.

Section 5. To be eligible to election to Associate Membership, an applicant must be actively interested in geophysics.

Section 6. To be eligible to election to Student Membership an applicant must be a graduate or undergraduate student in good standing in residence at a recognized university or college.

Section 7. An Honorary Member or Active Member shall enjoy all privileges of the Society. He shall be eligible to hold any office, to vote on all matters submitted to the membership, to petition the Council or Executive Committee on any matter, to sponsor applicants for membership and to publish his affiliation with the Society.

Section 8. An Associate Member or Student Member shall be entitled to attend the meetings of the Society, to receive its journal and to purchase its publications, on the same terms as an Active Member. He shall have none of the other privileges of membership and in publishing his affiliation with the Society shall clearly indicate his grade of membership.

Article IV. Code of Ethics

Section 1. Membership of any class shall be contingent upon conformance with the established principles of professional ethics.

Article V. Election, Resignation and Expulsion of Members

Section 1. The method of election to the various grades of membership shall be as set forth in the Bylaws.

Section 2. Any member in good standing may resign from the Society at any time as set forth in the Bylaws.

Section 3. Any member may for the good of the Society be suspended or expelled from the Society at any time as set forth in the Bylaws.

Article VI. Officers

Section 1. The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. Officers shall be elected in the manner prescribed in the Bylaws for a term of one year with the exception of the Editor, whose term shall be two years.

Section 2. Election of officers shall be by secret mail ballot. On the ballot shall be printed the nominees for each office arranged in alphabetical order.

Section 3. The Standing Committee on Nominations shall nominate, in the manner prescribed in the Bylaws, two candidates for each office to be filled. Further nominations may be made by petition as set forth in the Bylaws.

Section 4. The officers shall assume the duties of their respective offices immediately after the close of the Annual Meeting following their election.

Section 5. No officer shall be eligible for election to the same office for two consecutive terms.

Section 6. In case of a vacancy in any office, other than the President's, the Executive Committee shall select a successor to serve until the close of the Annual Meeting following this appointment.

Article VII. Duties of Officers

Section 1. The President shall be the presiding officer at all the meetings of the Society, shall take cognizance of the acts of the Society and of its officers, shall appoint such standing committees and special committees as are required for the purposes of the Society, and shall delegate members to represent the Society. He may, at his option, serve on, and may be chairman of, any committee. He shall prepare an address to be given before the members of the Society at the Annual Meeting.

Section 2. The Vice-President shall assume the office of President in case of a vacancy from any cause in that office and shall assume the duties of President in case of the absence or disability of the latter. He shall also be responsible for all national meetings of the Society.

Section 3. The Secretary-Treasuer shall assume the duties of the President in case of the absence of both the President and Vice-President. He shall have charge of the financial affairs of the Society and shall annually submit reports as Secretary-Treasurer covering the fiscal year, which he shall arrange to have published in the next regular issue of the journal of the Society. Under the direction of the Council, he shall arrange for the receipt and disbursal of all Society funds. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded, all employees to whom authority may be delegated to handle Society funds. The amount of such bonds shall be set by the Council and the expense shall be borne by the Society.

Section 4. The Editor shall be in charge of the editorial business, shall submit an annual report of such business, shall have authority to solicit papers and material for the regular Society publication and for special publications, and may accept or reject material offered for publication. He may appoint associate, regional, and special editors.

Article VIII. Council

Section 1. The Council of the Society shall consist of the officers, the Past President, the Prior Past President, and all elected District Representatives.

Section 2. The Council shall be the governing body of the Society and subject to the provisions of the Constitution and Bylaws shall have full control and management of the affairs and funds of the society.

SECTION 3. A joint meeting of the outgoing and incoming Councils shall be held at the call and under the chairmanship of the newly elected President during or within seven days after the Annual Meeting of the Society. At this joint meeting the Councils shall hear reports from all officers and committees and review the activities of the Society for the past year. With the advice of the outgoing Council, the incoming Council shall conduct any necessary business and issue instructions or recommendations to any officer or committee, subject to the provisions of the Constitution and Bylaws. All committee chairmen shall attend this meeting, but, as chairmen, shall have no vote.

SECTION 4. At the call of the President or a majority of the Council members, and after written notice to all Council members, the Council may meet at any time.

SECTION 5. A quorum at any meeting of the Council shall consist of six Council members.

SECTION 6. Unless otherwise provided by the Constitution, all actions by the Council shall require a majority vote of the members present.

ARTICLE IX. EXECUTIVE COMMITTEE

SECTION 1. The Executive Committee shall consist of the President, the Vice-President, the Secretary-Treasurer, the Editor, and the Past President.

SECTION 2. When the Council is not in session the Executive Committee shall have full authority, subject only to prior instructions by the Council, to exercise all powers of the Council.

SECTION 3. All actions of the Executive Committee shall require a majority vote of all members of the Committee.

SECTION 4. The Executive Committee may vote an any matter either by mail or in person.

ARTICLE X. MEETINGS

SECTION 1. The Society shall hold at least one meeting of the members each year, this meeting to be known as the Annual Meeting. One session of this meeting shall be a Business Meeting, at which reports of the officers and committees shall be read and the result of the mail ballot for officers announced.

SECTION 2. The Annual Meeting shall be held at a time and place designated by the Executive Committee.

SECTION 3. Additional meetings of the Society may be called by the Executive Committee.

ARTICLE XI. LOCAL SECTIONS

SECTION 1. Local sections, consisting of members of the Society and other persons engaged in geophysics or a related field residing within an appropriate distance of a central point, may be organized as provided in the Bylaws.

SECTION 2. Each local section shall assist in carrying out the objectives of the Society within the territory assigned to the section by the Council.

SECTION 3. Each local section shall have one District Representative if among its members there are less than seventy-five Honorary Members and Active Members of the Society in good standing, two District Representatives if more than seventy-five and less than one hundred fifty, or three District Representatives if more than one hundred fifty.

SECTION 4. The District representatives shall be elected from among the Honorary Members and Active Members of the Society in good standing for terms stated and in the manner prescribed in the By laws and shall not be eligible for two consecutive terms.

ARTICLE XII. DISTRICTS

SECTION 1. The Council shall divide the area of the continental United States, not assigned to local sections, into not more than seven districts. Council may designate districts outside the area of the continental United States.

SECTION 2. Each district shall have for each seventy-five Active Members of the Society, who are not members of a local section, one District Representative, who shall be appointed by the President for a term of one year expiring at the close of the Annual Meeting.

Article XIII. Affiliated Societies

Section 1. The Council may arrange for affiliation of the Society with any duly organized groups or societies.

Section 2. The terms of affiliation must provide that the Society shall have the right to dissolve such affiliation at any time, subject only to the payment of any sums it may legally owe the affiliated group or society.

Article XIV. Committees

Section 1. In addition to the Executive Committee, there shall be appointed standing committees to further the purposes of the Society.

Section 2. The duties of the standing committees and the method of their appointment shall be in accordance with the Bylaws.

Section 3. The President may at any time appoint special committees for such purposes as he may deem fit.

Section 4. The terms of all special committees shall expire at the close of the Annual Meeting following their appointment.

Article XV. Business Manager

Section 1. The Council may employ a business manager for the Society and pay him such salary and other compensations from the Society's funds as they deem advisable.

Section 2. The business manager shall provide a bond appropriate in amount, the cost to be borne by the society.

Section 3. The business manager shall, under the supervision of the Secretary-Treasurer, perform such duties as the Council may assign him.

Section 4. The Council may discharge the business manager at any time.

Article XVI. Review by Members

Section 1. All acts of the officers, Council, and committees of the Society shall be subject to review by the members.

Section 2. Proposals to change any decision, policy, or procedure of any officer, the Council, or any committee shall be submitted in writing to the President and signed by at least twenty-five Honorary and Active Members in good standing.

Section 3. Upon receipt of such a petition with a sufficient number of valid signatures, the President shall advise the Council and the officer or committee involved.

Section 4. Should the officer or committee involved be unwilling to comply with the petition, it, together with a discussion by the proposer and the officer or committee involved, shall be published in the next issue of the Society's journal.

Section 5. Within thirty days after publication in the journal, the petition shall be submitted to the membership by mail ballot by the President. A majority of the ballots returned within thirty days after being mailed by the President shall be decisive. Should the vote favor the petition, it shall be complied with, within the limitations imposed by the Constitution and Bylaws, as promptly as practicable.

Article XVII. Bylaws

Section 1. The Council shall make such Bylaws not in conflict with the Constitution, as it may deem necessary for the proper government of the Society. The Council may amend the Bylaws at the annual joint meeting by an affirmative vote of two-thirds of the members of the incoming Council present. All proposed amendments must, however, be published in the Society's journal before being submitted to the Council.

Article XVIII. Amendments to the Constitution

Section 1. Amendments to this Constitution may be proposed by any ten members of the Society, by any officer of the Society, or by a Constitutional Committee appointed by the President.

Section 2. Any proposed amendment shall be submitted to the President in time for publication in the Society's journal prior to the Annual Meeting.

Section 3. At the annual joint meeting of the Council, all proposed amendments received since the previous Annual Meeting, shall be considered. Those receiving approval from a majority of the members of the incoming Council present shall be submitted by mail ballot, arranged by the Secretary-Treasurer, to the entire membership of the Society within sixty days. If a majority of the ballots returned within sixty days of their mailing favor the proposed amendment, it shall become effective at the expiration of this sixty days. All amendments shall be reported in the Society's journal.

BYLAWS

(As amended to July 16, 1954)

Article I. Publications
Article II. Election of Honorary Members
Article III. Election of Active, Associate and Student Members
Article IV. Dues
Article V. Resignation of Members
Article VI. Expulsion of Members
Article VII. Election of Officers
Article VIII. Local Sections
Article IX. Finances of Local Sections
Article X. Standing Committees

Article I. Publications

Section 1. The Society shall publish a journal entitled Geophysics.

Section 2. The journal shall be published at intervals designated by the Executive Committee.

Section 3. All reports to the Society by its officers and committees shall be published in the journal. All members of the Society shall be presumed to have due notice of all Society matters published in the journal. Each issue shall contain a membership list of all standing and special Committees.

Section 4. Original papers, reviews, abstracts, notes or letters containing information deemed by the Editor to be of interest to the members of the Society shall be published in the journal. The Editor shall be the sole judge of whether such material is to be published.

Section 5. The subscription rate of the journal shall be $9.00 ($9.50 foreign) per year to nonmembers and $4.50 per year to members. The first $4.50 of the annual dues of each dues paying member shall be set aside for the payment of his subscription to the journal. Members of affiliated societies shall be entitled to receive the journal upon payment of a fee equivalent to the dues charged to an associate member.

Section 6. The Council may at its annual joint meeting authorize the printing of special publications to be financed and distributed in a manner approved by the Council.

Article II. Election of Honorary Members

Section 1. The Standing Committee on Honors and Awards may submit to the President ninety days before the Annual Meeting the names of any person or persons they deem eligible to election as an Honorary Member. Their report shall explain the basis of their recommendation.

Section 2. The President shall submit copies of any such reports to all members of the Council not less than sixty days before the Annual Meeting.

Section 3. The Council members shall consider all such reports and vote by mail thirty days before the Annual Meeting. Unanimous action by those voting shall be required to elect any person as an Honorary Member.

Article III. Election to Active, Associate, and Student Membership

Section 1. An applicant for election to Active, Associate, or Student Membership shall submit to the business manager of the Society an application setting forth in detail his education and experience. The application shall list the names and present addresses of persons who can verify the statements given therein. It shall list not less than three Active Members or Honorary Members of the Society, in good standing, who are personally acquainted with the training or experience of the applicant. This application shall be open to inspection at any time.

Section 2. The Executive Committee may waive the requirement of references from members of the Society for geographical or other reasons, if the applicant is otherwise eligible and furnishes other satisfactory references.

Section 3. The business manager shall write to all references for verification of the applicant's statements. All replies from references shall be considered confidential and shall not be disclosed except to the Executive Committee, without the references' prior written consent.

Section 4. The name of each applicant for Active membership shall be published in the next regular issue of the Society's journal for approval by the membership at large. If no objection is received within thirty days after this publication, the applicant shall be deemed approved by the membership at large.

Section 5. An applicant for Active or Associate membership must be approved by a majority of the Executive Committee. An applicant for Student membership must be approved by the Secretary-Treasurer.

Section 6. When an applicant has been approved, he shall be notified in writing by the Business Manager. If he fails to make payment of full annual dues within four months after such notification, the Executive Committee may rescind his election. His membership shall date from the first day of the calendar year in which he makes his initial payment of dues and he shall receive the regular Society publications for that year.

Section 7. An Associate or Student Member may seek transfer to Active Membership by supplying added information to show that he has become eligible to election to Active Membership. The transfer shall be handled in the same manner as election to Active Membership. The Standing Committee on Membership may of its own initiative secure the necessary added information and submit it to the Executive Committee.

Article IV. Dues

Section 1. Honorary members shall not be required to pay dues and shall receive the journal and other publications without charge.

Section 2. The annual dues of an Active or Associate Member of the Society shall be seven dollars and fifty cents ($7.50), which includes the cost of one subscription to the Society's journal.

Section 3. The annual dues of a Student Member of the Society shall be four dollars and fifty cents ($4.50), which includes the cost of one subscription to the Society's journal.

Section 4. Annual dues shall be payable in advance on January 1 of the calendar year. A bill shall be mailed to each Active, Associate, or Student Member before that date, stating the amount of annual dues and the penalty for default. The Society's journal shall be withheld from members pending payment of dues, and Active Members failing to pay by ten days prior to the Annual Meeting shall have their votes in the annual mail ballot disqualified. Members in arrears shall lose all privileges of membership until such arrears are met.

Article V. Resignation of Members

Section 1. Any member of the Society may resign at any time. Such resignation shall be submitted in writing to the Council.

Section 2. Any member who resigns under the provisions of Section 1 of this Article ceases to have any rights in the Society and ceases to incur further indebtedness to the Society.

Section 3. Any person who has ceased to be a member under Section 1 of this Article may be re-

instated by unanimous vote of the Executive Committee subject to the payment of any outstanding dues and obligations which were incurred prior to the date when he ceased to be a member of the Society.

Article VI. Expulsion of Members

Section 1. Any member who fails to pay his dues by the last day of the calendar year shall be automatically suspended from membership on that day. While he is suspended, he shall have no rights in the Society and shall not be charged any dues.

Section 2. A member who has been suspended more than one year shall be dropped from the Society by the Executive Committee.

Section 3. A suspended member will automatically be reinstated by payment of outstanding dues and obligations and the dues for the current calendar year.

Section 4. A member who has been dropped under the provisions of Section 2 of this Article may be reinstated by a majority vote of the Executive Committee subject to the payment of outstanding dues and obligations and the dues for the current calendar year.

Section 5. Any member who, after being granted a hearing by the Executive Committee, shall be found guilty of a violation of the established principles of professional ethics, or shall be found guilty of having made a false or misleading statement in his application for membership in the Society, shall be asked to resign from the Society by unanimous vote of the Executive Committee. The decision of the Executive Committee in all matters pertaining to the interpretation and execution of the provisions of this section shall be final.

Article VII. Election of Officers

Section 1. The Standing Committee on Nominations shall consist of the President, the Past President, and the Prior Past President.

Section 2. The Standing Committee on Nominations shall nominate two or more candidates for each office to be filled. They must secure the consent of all candidates nominated.

Section 3. The Standing Committee on Nominations must submit their ticket to the President in time for publication in the April issue of the Society's journal.

Section 4. Prior to June 1, nominations in writing, signed by at least twenty Honorary Members or Active Members in good standing and accompanied by the written consent of the candidate, may be submitted to the President.

Section 5. Between June 1 and June 15, the Business Manager will prepare and mail to each member eligible to vote, a ballot listing all candidates properly nominated for each office. With each ballot, the business manager shall send an official envelope having the member's name on the back.

Section 6. The Standing Committee on Nominations shall appoint a committee of tellers to count the ballots.

Section 7. Each member voting may cast one vote for each officer and shall return his ballot to the business manager in the official envelope carrying on the outside the written signature of the member submitting the ballot. Only ballots so prepared by members in good standing, and received by the business manager at his officially recognized address not later than July 31, shall be valid.

Section 8. The business manager shall indicate which ballots are valid, and shall deliver all ballots unopened to the tellers after August 1. The candidate receiving the greatest number of valid votes cast for an office shall be declared elected to that office. In case of a tie, the Standing Committee on Nominations shall decide by a secret vote which of the candidates shall be elected. Results of the mail ballot shall be communicated to all candidates by the nominating committee on or before August 15.

Article VIII. Local Sections

Section 1. Upon petition of twenty members in good standing residing within an appropriate distance of a central point, the Council may authorize the formation of a Local Section and assign a specific territory to the Local Section. The Council may decline to authorize the formation of a Local

Section when in its judgment such an organization would not be compatible with the interests of the Society.

SECTION 2. In the organizing meeting of the section, all members of the Society residing in the territory assigned by the Council to the section shall be eligible to vote.

SECTION 3. The section shall be known as "The (name of place) Section of the Society of Exploration Geophysicists."

SECTION 4. The principal work of a section shall be the holding of regular meetings for the presentation and discussion of papers of interest to its members.

SECTION 5. The section shall adopt bylaws which must be approved by the Council of the Society and shall be consistent with the Constitution and Bylaws of the Society.

SECTION 6. The election of District Representatives by the Local Sections shall be by secret ballot. The term of office of a District Representative shall be two years; however, if the section is entitled to more than one representative, one of the representatives elected at the establishment of the section or added as the result of subsequent growth of the Section, shall be elected for a one year term if this is necessary to prevent the terms of all District Representatives from expiring simultaneously.

SECTION 7. District Representatives shall be elected at least three weeks prior to the Annual Meeting of the Society and shall take office at the close of the Annual Meeting.

SECTION 8. The Secretary of the Local Section shall submit to the Secretary-Treasurer of the Society a report of each meeting of the Local Section or its governing board within two weeks after the meeting. He shall submit to the Secretary-Treasurer of the Society the names of all officers and committee members within two weeks after their election or appointment.

SECTION 9. Any Local Section which for two consecutive years has among its membership fewer than twenty members in good standing of the Society shall automatically be dissolved by the Council at its annual joint meeting. The Council may at any time dissolve any Local Section for reasons it deems good and sufficient.

ARTICLE IX. FINANCES OF LOCAL SECTIONS

SECTION 1. The Society may, at the discretion of the Council, pay any portion of the necessary operating expenses of a Local Section up to the sum of the following amounts: (a) $100 per year; (b) $50 per meeting up to four meetings per year; (c) $0.50 per member of the Society.

SECTION 2. The Treasurer of the Local Section shall forward, from time to time, his application for such portions of the sum provided in Section 1 as may be needed to the Secretary-Treasurer of the Society, who will arrange for the issuance of a check for the requested amount to the Treasurer of the Local Section.

SECTION 3. Prior to the Annual Meeting, the Treasurer of each Local Section shall transmit to the Secretary-Treasurer of the Society, for approval by the Council, an itemized statement of the expenditure of the funds received from the Society during the preceding calendar year.

SECTION 4. Allocations to a Local Section for the year in which it is established shall be in proportion to the fraction of the calendar year remaining.

SECTION 5. The Local Section may levy dues or raise funds in any other manner, subject to the approval of the Council. Payment of local dues shall, however, not be a prerequisite to participation in any activity financed wholly or in part with funds received from the Society.

ARTICLE X. STANDING COMMITTEES

SECTION 1. The Society shall have the following standing committees: (a) Standing Committee on Nominations; (b) Standing Committee on Membership; (c) Standing Committee on Honors and Awards; (d) Standing Committee on Publications; (e) one or more General Committees for the Annual Meetings; (f) Standing Committee on Education; (g) Standing Committee on Student Membership; (h) Standing Committee on Distinguished Lectures; (i) Standing Committee on Radio Facilities; (j) Standing Committee on Reviews; (k) Standing Committee on Public Relations; (l)

Standing Committee on Publicity; (m) Standing Committee on Geophysical Activity; and (n) Standing Committee on Safety.

SECTION 2. Each standing committee shall have a chairman, appointed by the President unless otherwise specified in these Bylaws. The chairman shall submit a report to the President of the Society at such intervals as the chairman may deem advisable but at least quarterly. He shall submit to the Council at its annual joint meeting a report covering the activities of the committee since the previous Annual Meeting.

SECTION 3. The Standing Committee on Nominations shall consist of the President who shall be chairman, the Past President, and Prior Past President. Its duties shall be to nominate candidates for officers, appoint tellers to count the ballots, and to declare the election of the officers as prescribed in Article VII of these Bylaws.

SECTION 4. The Standing Committee on Membership shall consist of three Active or Honorary Members appointed for a period of one year by the President immediately following the Annual Meeting. One of the members appointed shall have been a member the preceding year. The Committee shall actively solicit applications for membership from those qualified. It shall work closely within the membership committees of the Local Sections.

SECTION 5. The Standing Committee on Honors and Awards shall consist of five Active or Honorary Members, none of whom shall have been members of the Society less than five years. The senior member of the committee shall retire after the Annual Meeting. Vacancies shall be filled by the President. The Committee shall recommend candidates for election to Honorary Membership to the Council. The Committee shall recommend to the Council the establishment of honors and awards and shall recommend candidates for all established honors and awards of the Society to the Council.

SECTION 6. The Standing Committee on Publications shall consist of five Active or Honorary Members who shall serve a two year term concurrent with the Editor and who shall be appointed by the Editor. The committee shall have the duty of advising and assisting the Editor. The Editor shall appoint the chairman of this committee.

SECTION 7. The General Committee for the Annual Meeting to be held in a given year shall consist of a General Chairman and such additional persons as he may deem desirable. The General Chairman shall be appointed by the President with the concurrence of the Vice-President one or more years in advance of the Annual Meeting for which he is responsible and shall serve until the completion of all business related to the Annual Meeting. The other members of the General Committee, the Chairman and members of any Committees to handle specific phases of the Annual Meeting shall be appointed by the General Chairman. The General Committee for the Annual Meeting shall have the duty of arranging and holding the Annual Meeting at a time and place designated by the Executive Committee.

SECTION 8. The Standing Committee on Education shall consist of five persons appointed for one year by the President. The chairman shall be an Active or Honorary Member. The committee shall promote effective geophysical education.

SECTION 9. The Standing Committee on Student Membership shall consist of five persons appointed for one year by the President. The chairman shall be an Active or Honorary Member. The committee shall encourage the interest of students in geophysics and the Society.

SECTION 10. The Standing Committee on Distinguished Lectures shall consist of six persons appointed for three years by the President. The two senior members of the committee shall retire after the Annual Meeting. The chairman of the committee shall be appointed for one year by the President, and shall be an Active or Honorary Member. The committee shall obtain distinguished lecturers in geophysics and plan and supervise tours by these lecturers to the Local Sections of the Society and other participating organizations.

SECTION 11. The Standing Committee on Radio Facilities shall consist of from 5 to 15 Active or Honorary Members appointed for one year by the President. The committee shall, upon request from its chairman, determine the opinions of the members of the geophysical industry concerning matters pertaining to the use of radio in geophysics.

SECTION 12. The Standing Committee on Reviews shall consist of from 5 to 10 members who

need not be Active Members of the Society. The members and the chairman shall serve a two year term concurrent with the Editor and shall be appointed by the Editor. The committee shall prepare reviews of current geophysical literature for publication in GEOPHYSICS.

SECTION 13. The Standing Committee on Public Relations shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall advise the officers and Council of the Society concerning matters pertaining to public relations, shall recommend public relations policy, and shall carry out projects to promote good public relations.

SECTION 14. The Standing Committee on Publicity shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall prepare and arrange for the distribution of suitable publicity material for the press, radio, and other appropriate media.

SECTION 15. The Standing Committee on Geophysical Activity shall consist of four or more Active or Honorary Members of the Society appointed for a term of one year by the President. The committee shall conduct an annual survey of geophysical activities throughout the world. This report shall be presented before the Society at its Annual Meeting and published in the January issue of GEOPHYSICS. It may be made available for publication in leading trade journals for release at the time of the annual meeting.

SECTION 16. The Standing Committee on Safety shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall recommend safety policy and shall carry out projects to promote safety in geophysical operations.

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AAPG ANNOUNCES COMPETITION FOR OFFICIAL EMBLEM

The American Association of Petroleum Geologists has appointed an Official Emblem Committee with Mr. Merrill W. Haas as Chairman. The purpose is to adopt an official insigne or emblem for the Association.

Designs for such an emblem are solicited. The first prize will be $50.00 and the second prize $25.00. Anyone, whether a member or non-member, is eligible to submit an entry or entries. The designs may be in any form from a flat-type emblem suitable for letterheads, buttons, or flags, to a full scale with obverse and reverse sides. All entries will be judged without regard to type. Entries must be submitted prior to December 1, 1955, and will become the property of the AAPG. After a preliminary judging, the successful entries will be displayed at the Association's 1956 Meeting in Chicago for final selection of the first and second prize winners.

Entries should be sent to Mr. Merrill W. Haas, Chairman, Official Emblem Committee, AAPG, Box 801, Tulsa, Oklahoma.

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SPECIAL ANNOUNCEMENT

A few copies of the attractive SILVER ANNIVERSARY PROGRAM booklet distributed to registrants at the 25th Annual Meeting are available. The program contains a list of present and past officers and charter members of SEG, "A quarter century of the Society of Exploration Geophysicists and its historical background" by Paul L. Lyons, condensed program, biographies of recipients of Honorary Membership, and abstracts of papers and biographies of authors. It is $6\frac{3}{4}$ by $9\frac{1}{2}$ inches, bound in blue leatherette, and may be obtained at $3.00 per copy from the Society of Exploration Geophysicists, 624 South Cheyenne, Tulsa, Oklahoma.

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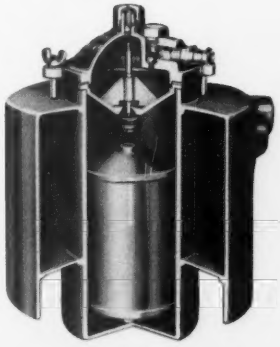

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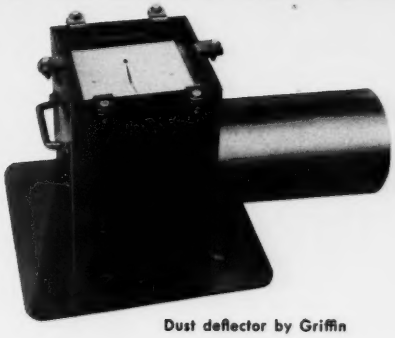

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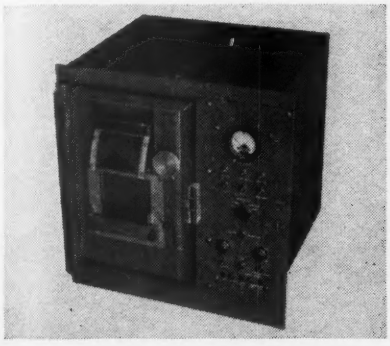

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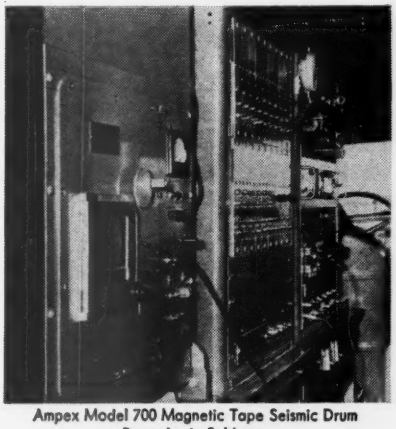

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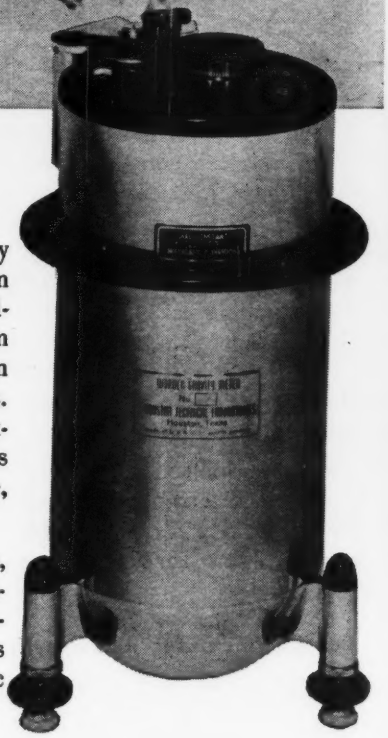

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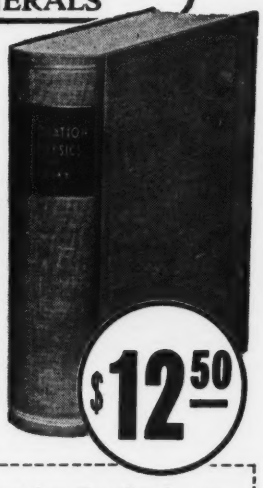

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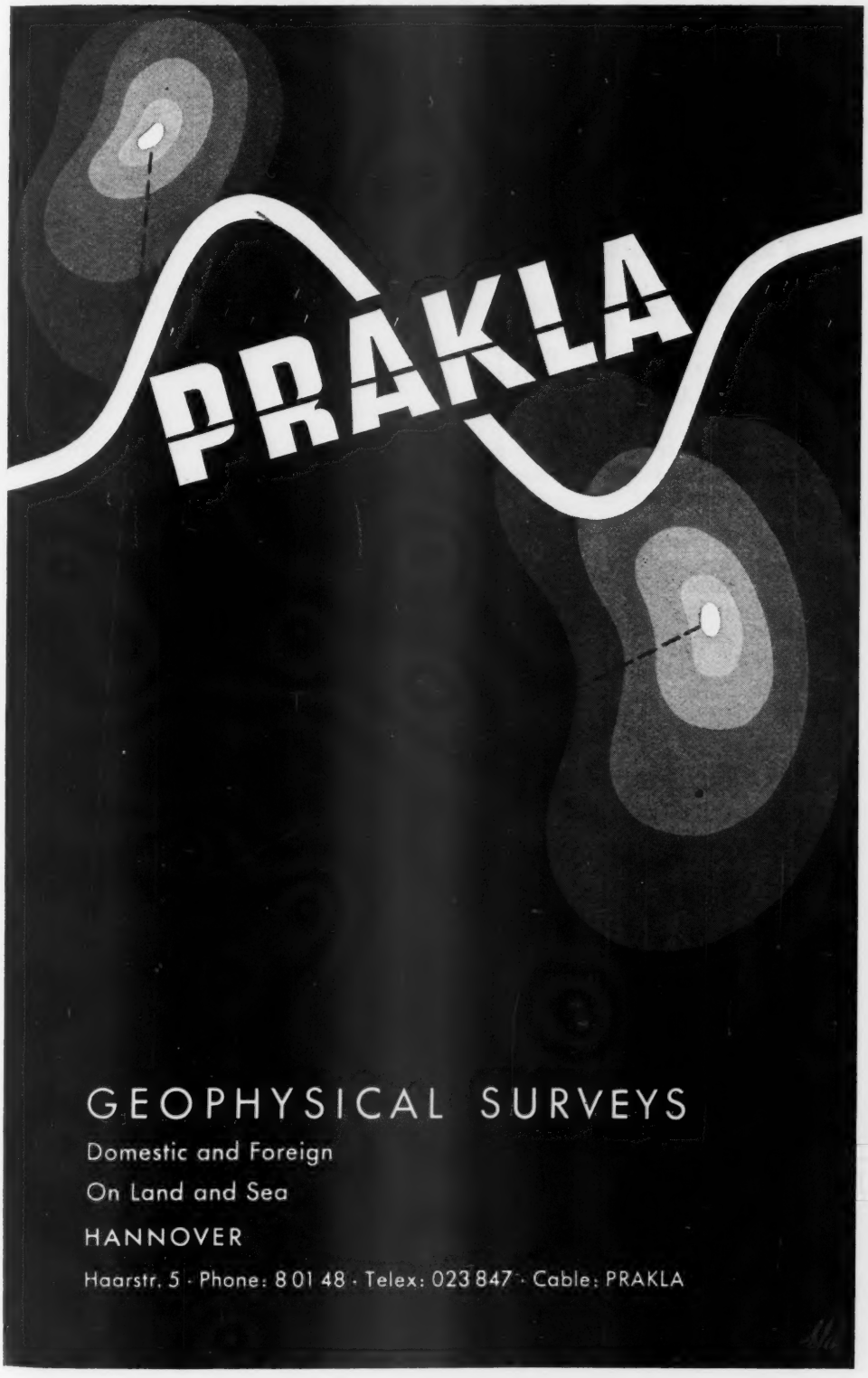
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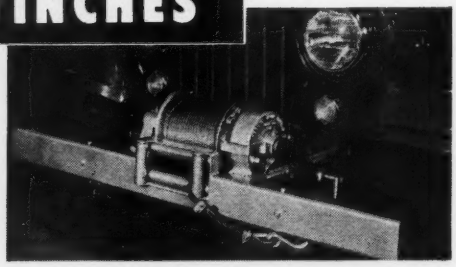

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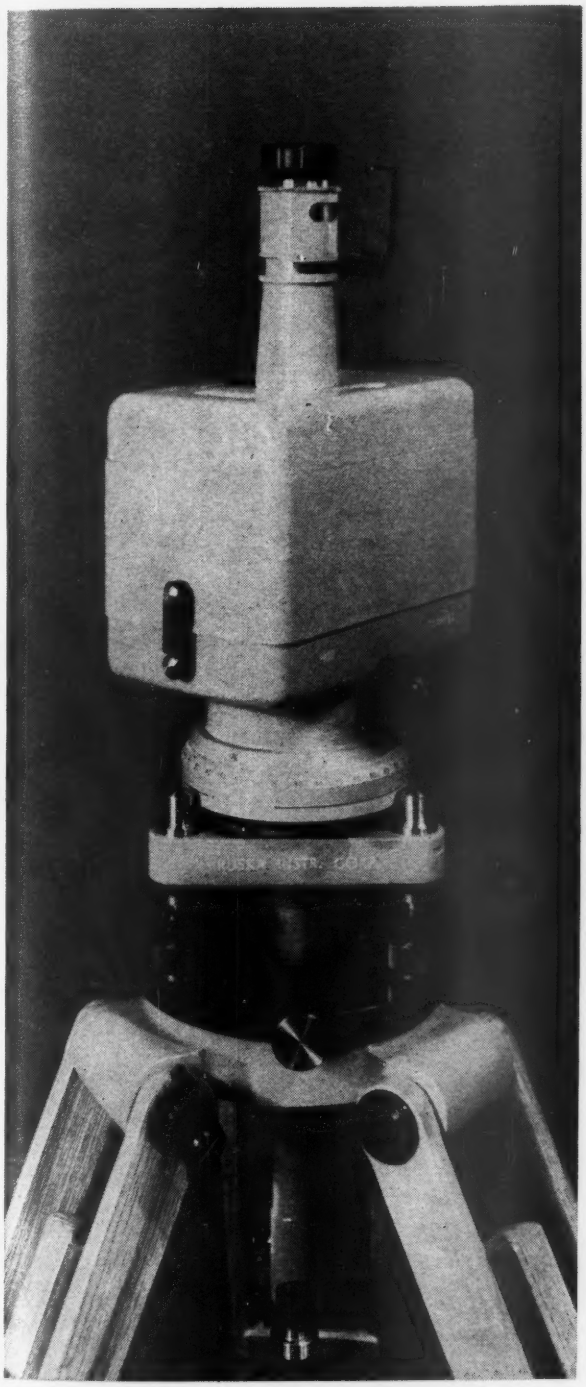

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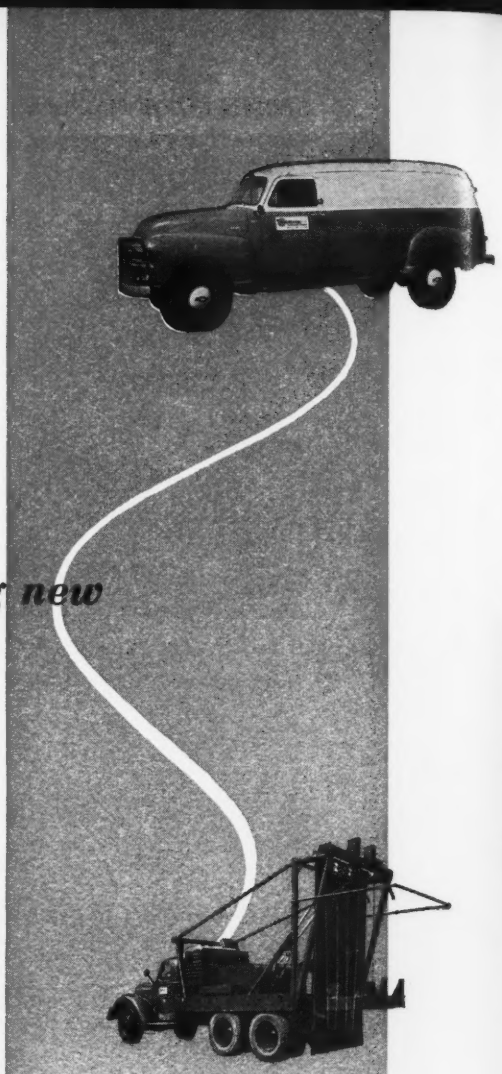

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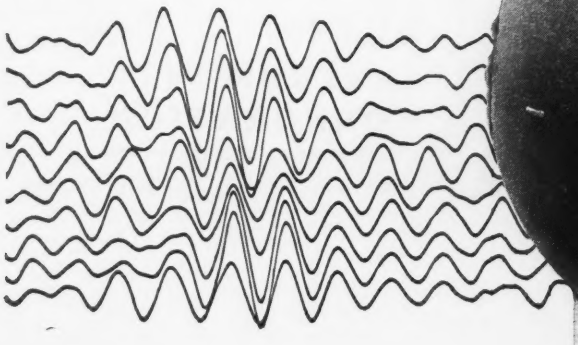

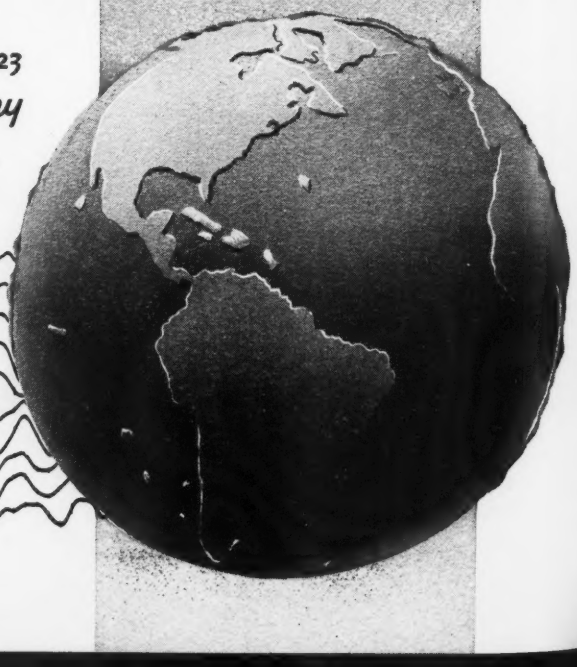

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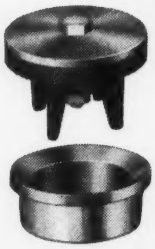

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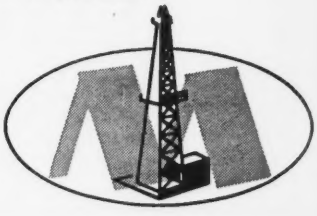

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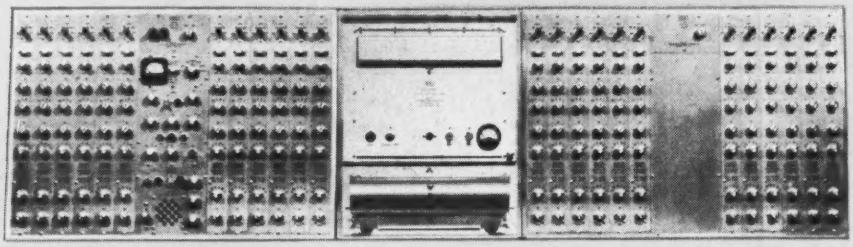

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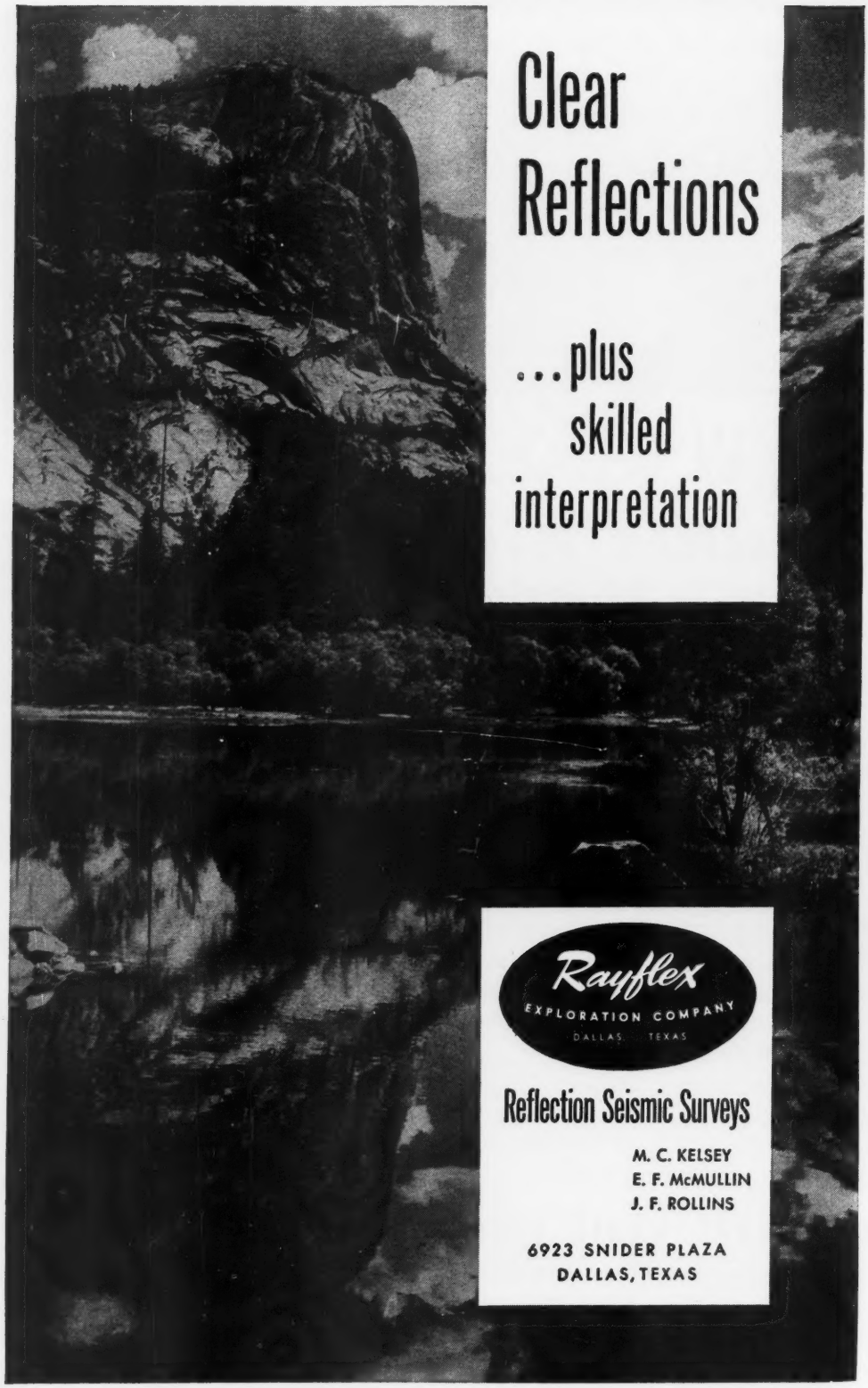
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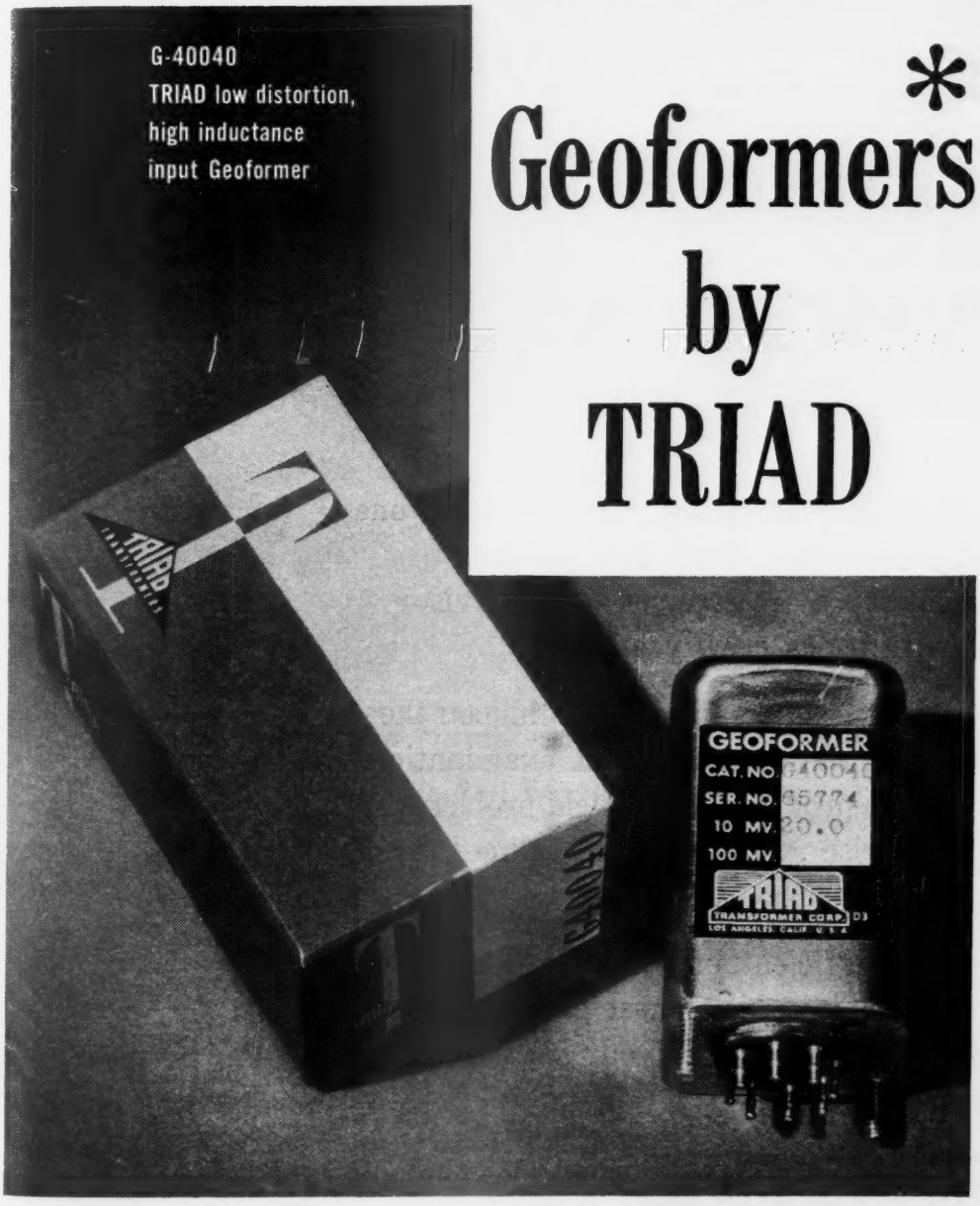

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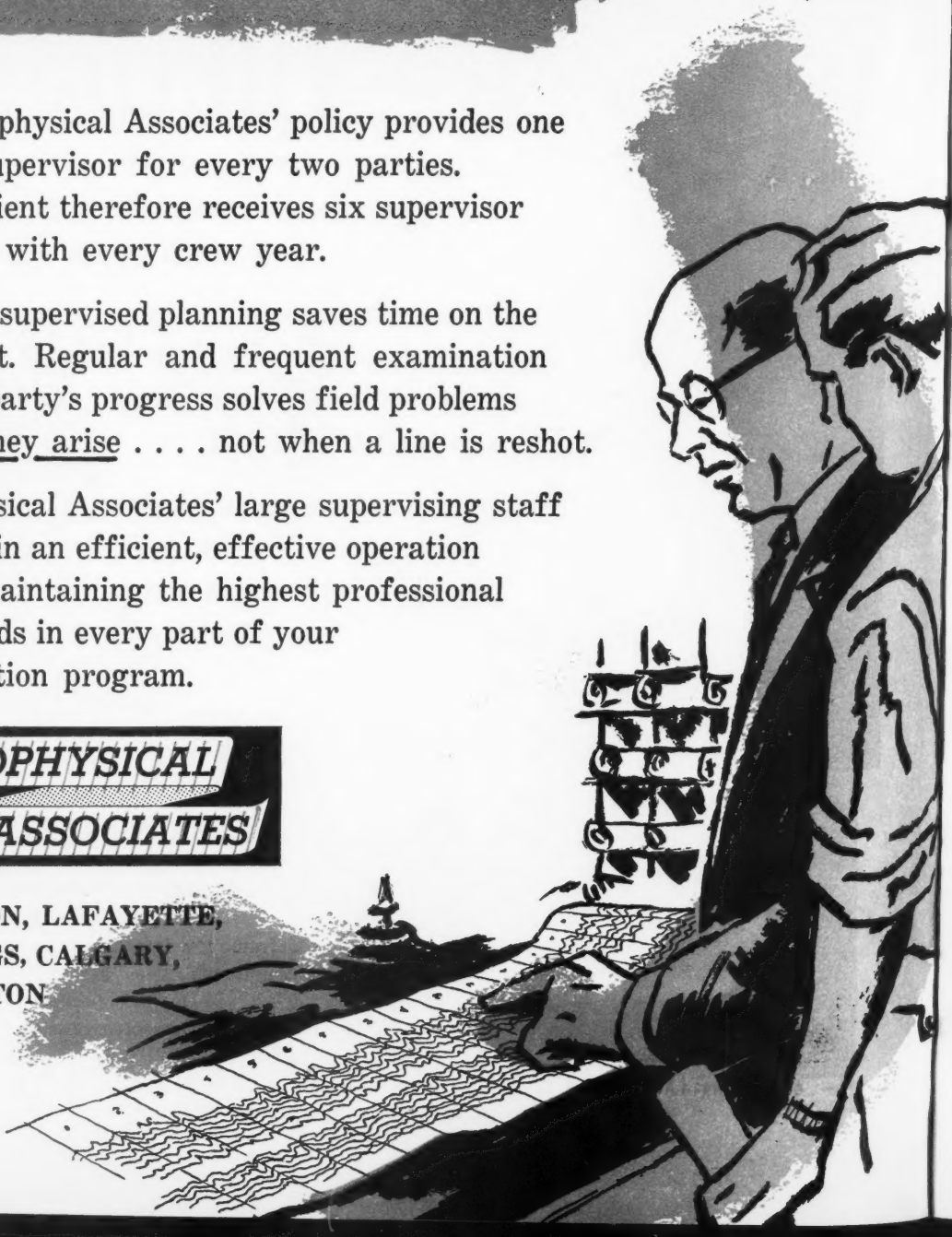

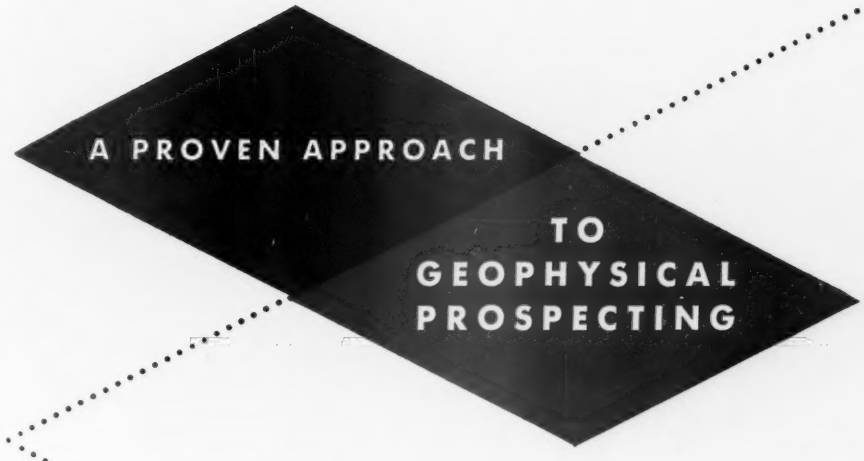

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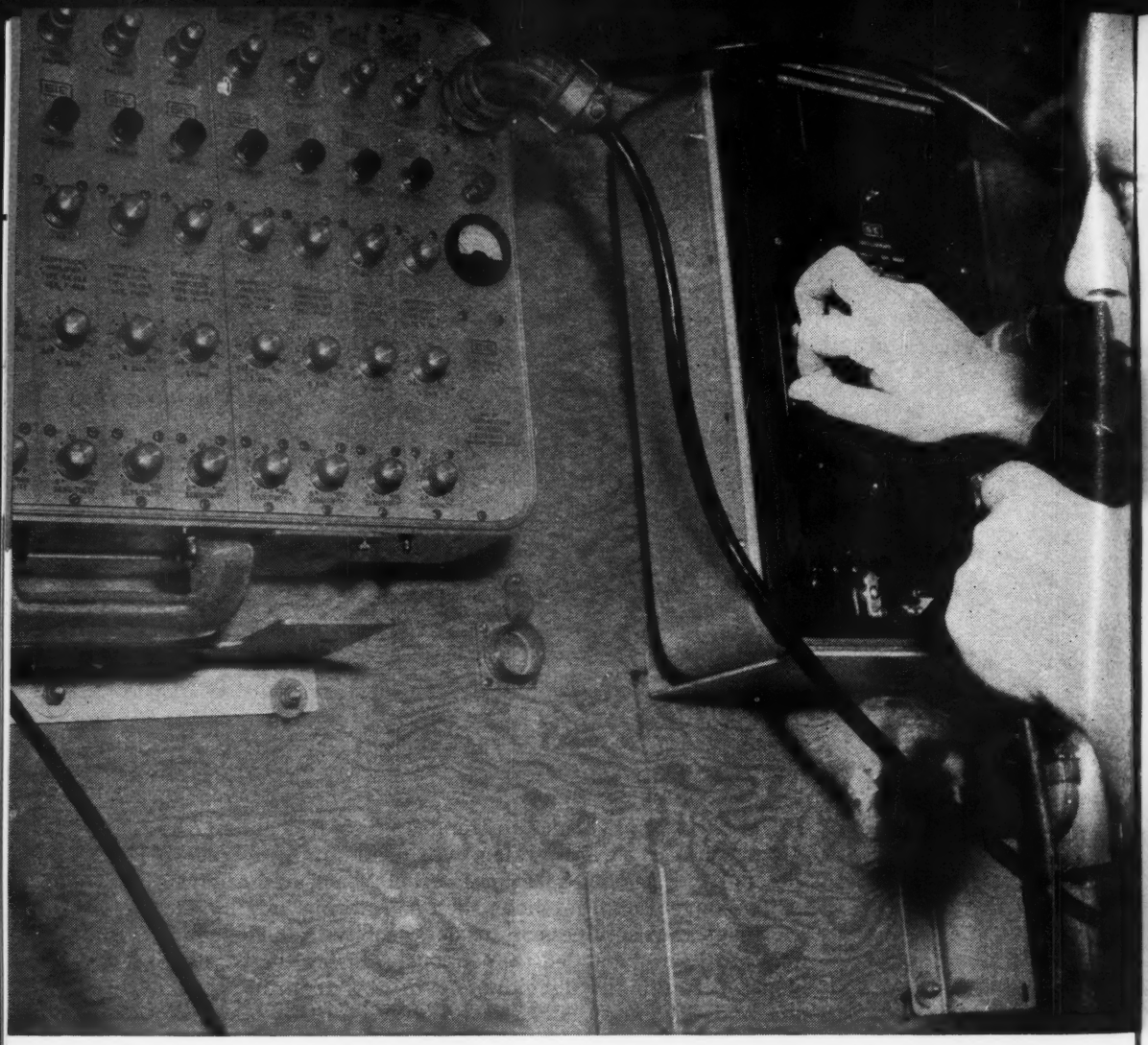

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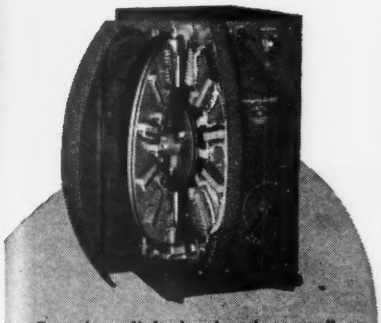

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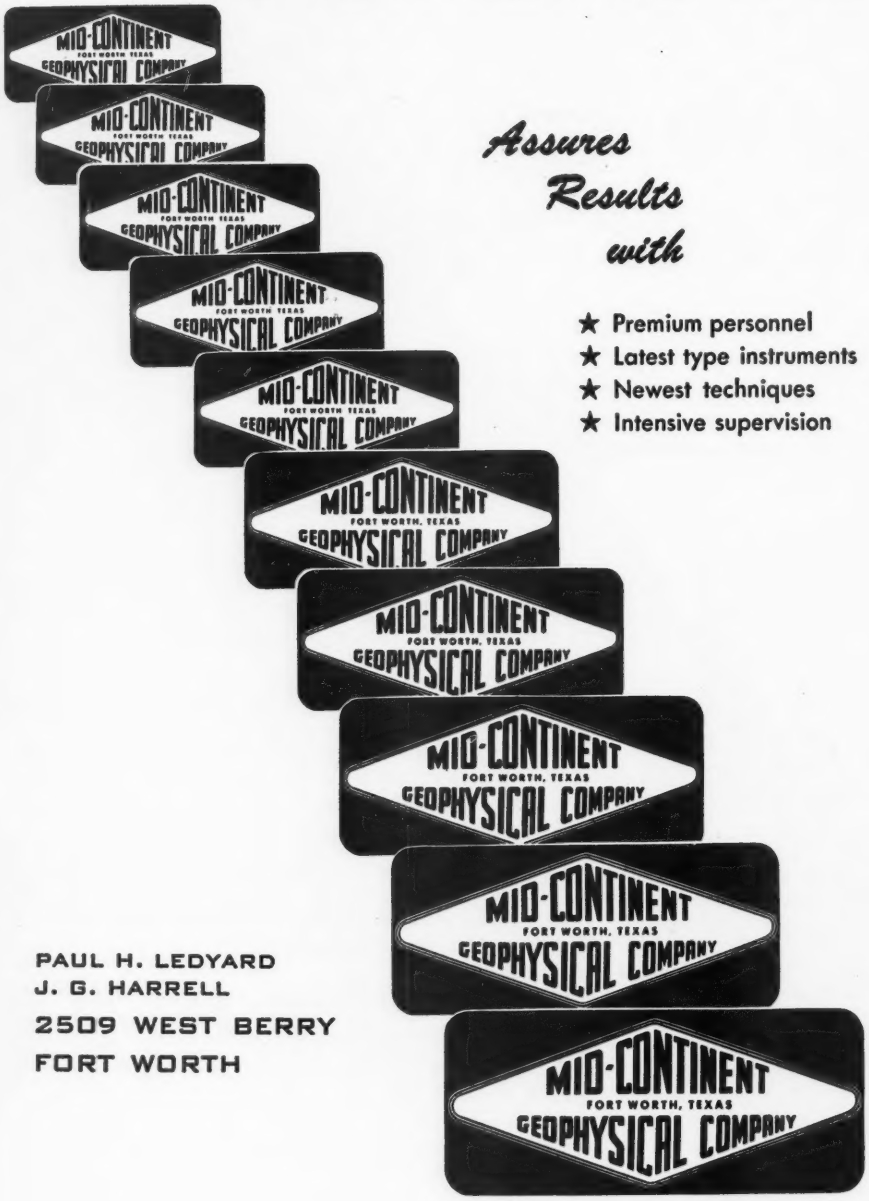

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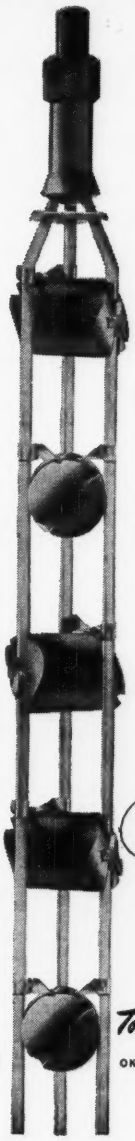

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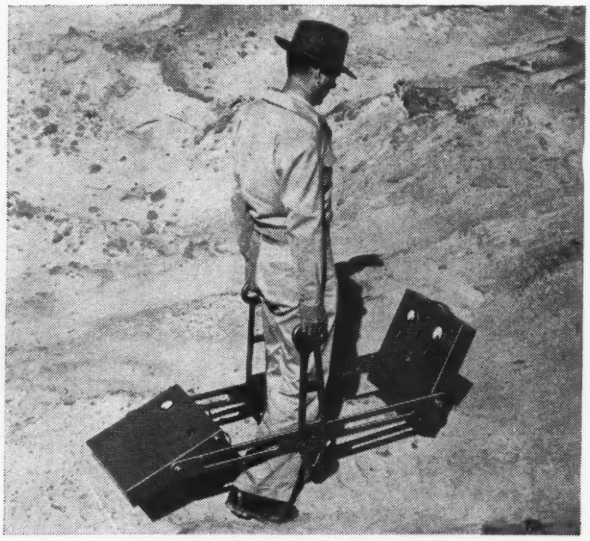

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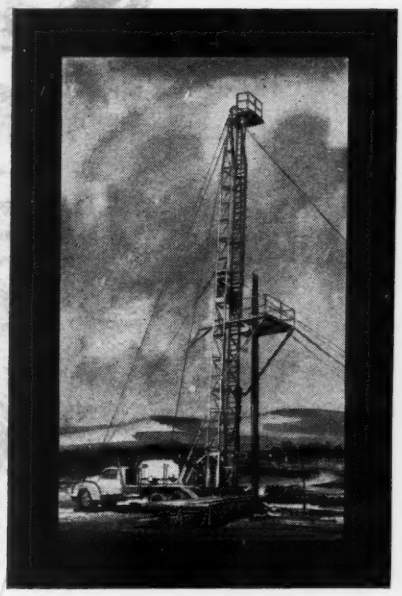

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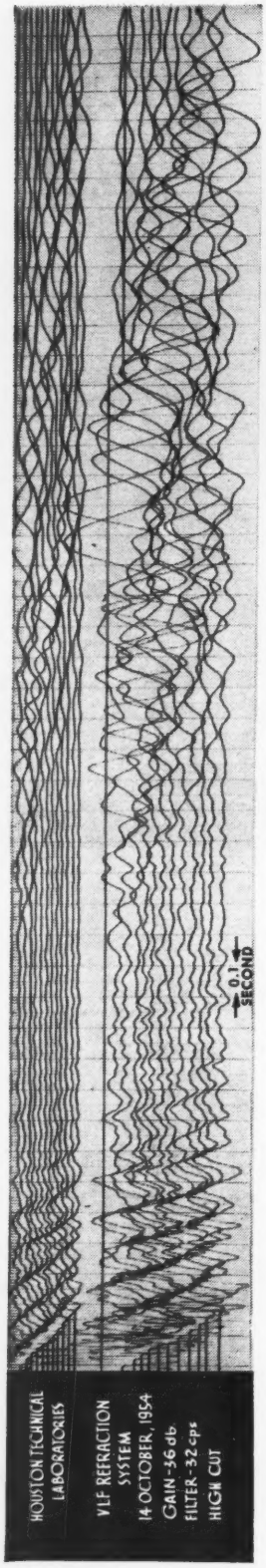

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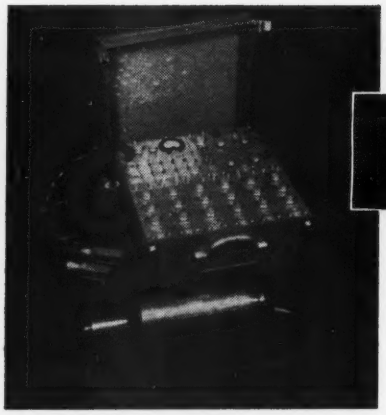

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The new Houston Technical Laboratories VLF (very low frequency) seismic refraction system is especially useful in areas unworkable with the reflection method. The VLF refraction system can be used in petroleum exploration, mining surveys, civil engineering, and ground water location and is capable of covering large areas quickly.

With excellent frequency response down to one cycle on the amplifiers and to two cycles on the seismometers, the VLF refraction system is exceptionally versatile in application. A combination of high cut filters provides a frequency cut-off range from 8 cps to 48 cps — low enough for good refraction work at extremely long ranges, yet high enough for all applications except those at extremely small ranges.

Excellent first breaks have been received at a distance of five miles using only a five pound charge.

Portability of the new VLF system is achieved through compact design of the 12-channel amplifier unit which measures 16¼ x 16⅞ x 8¼ inches and weighs only 42 pounds. Two output signals from each amplifier channel are recorded on a standard HTL RS-8 recording oscillograph, with paper speed adjustable from 7 to 16 inches per second.

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For detailed information about the new VLF seismic refraction system, write for Bulletin No. S-308.

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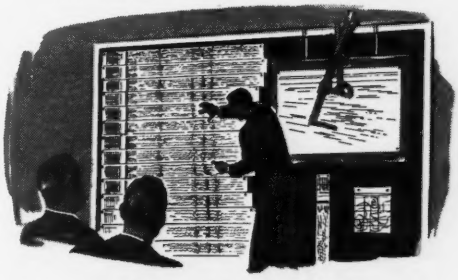
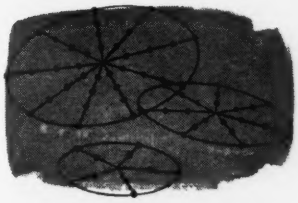


INTERPRETATION



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For twenty-three years, SEI has specialized in subsurface studies of the domestic oil provinces . . . from Canada to the Gulf. Numerous innovations in instrumentation, interpretation, and field technique have kept SEI in the forefront. For example, in difficult areas, SEI has been a pioneer in the use of patterns of multiple shot holes and geophone arrays.

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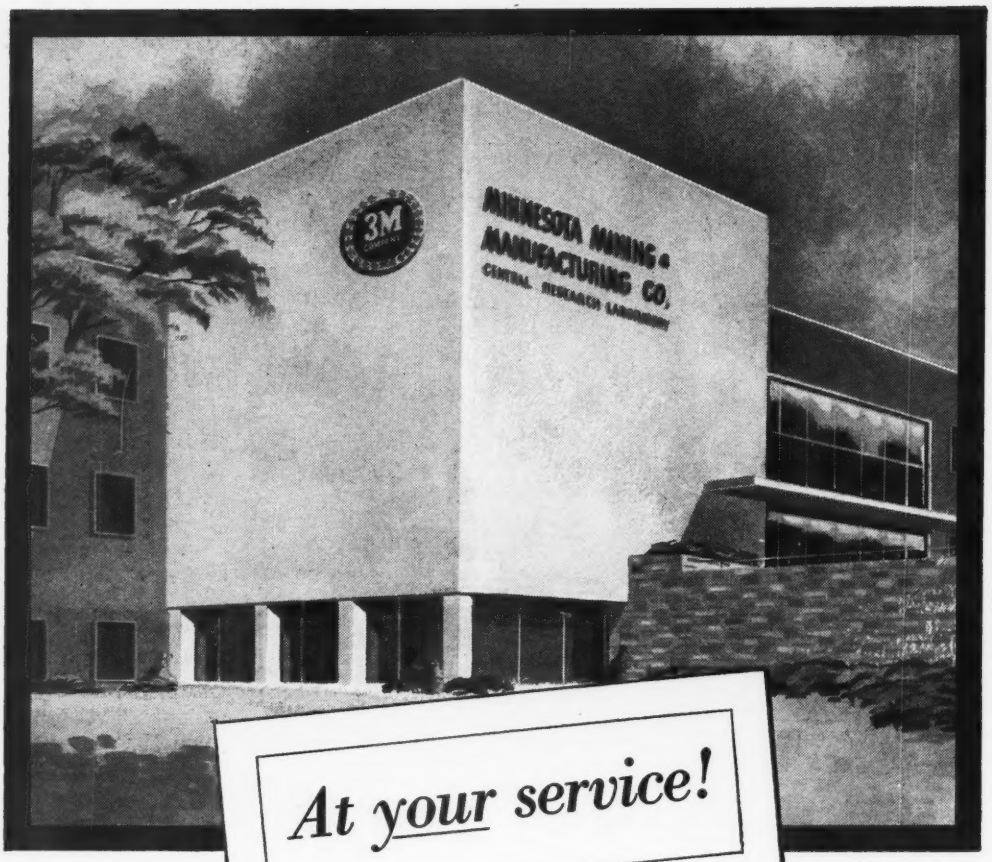

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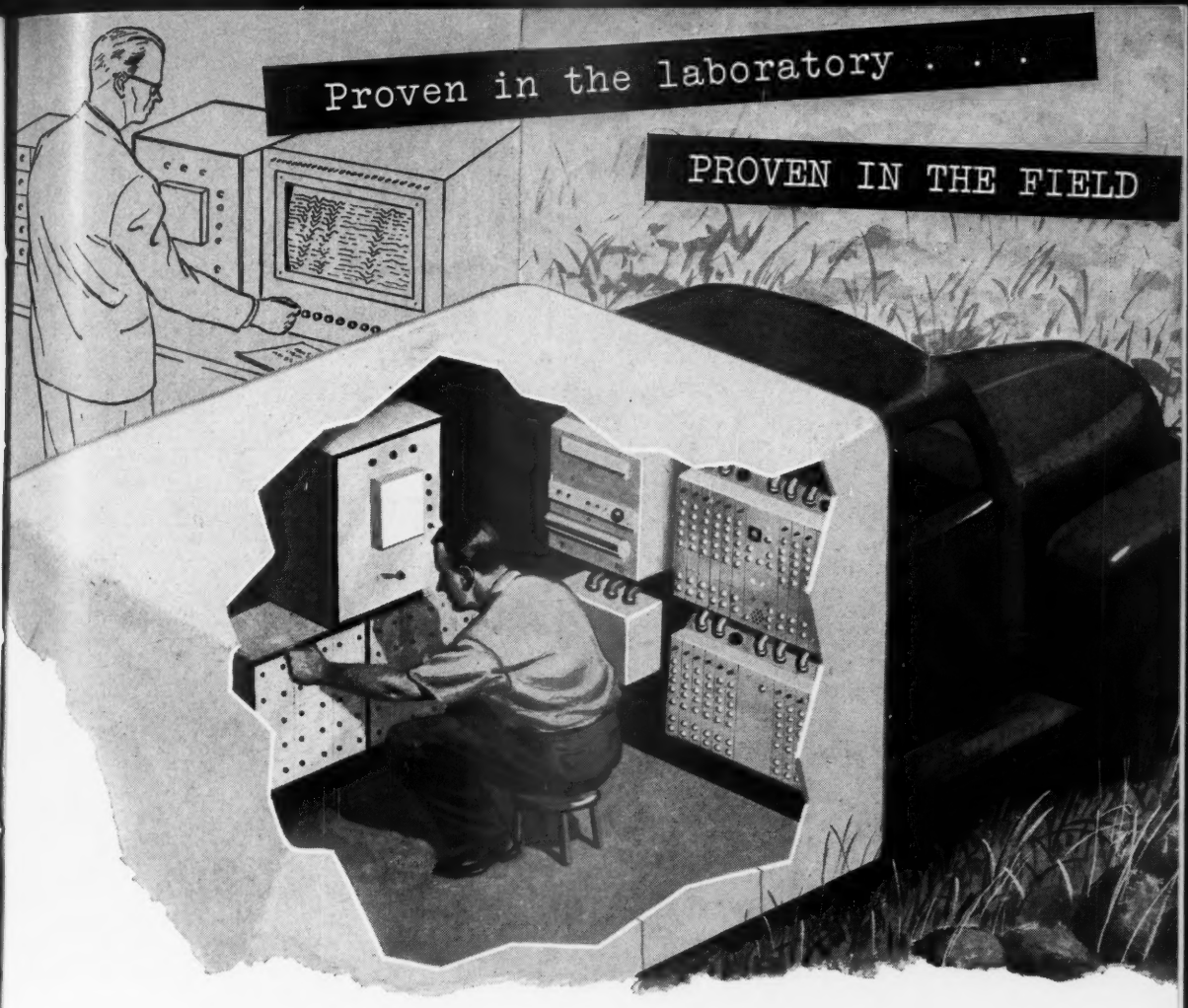

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Frequency Range: 1 to 500 cps.

Signal-to-noise ratio: 46db peak to peak without noise cancelling circuit from 1 cps to 500 cps.
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Distortion: Less than 1%.

Specifications

Record Length: 5½ seconds

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Channels: 24 data. 4 control.

Power Source: 12 volts DC

Recorder Dimensions: 21⅜"x15⅝"x17".

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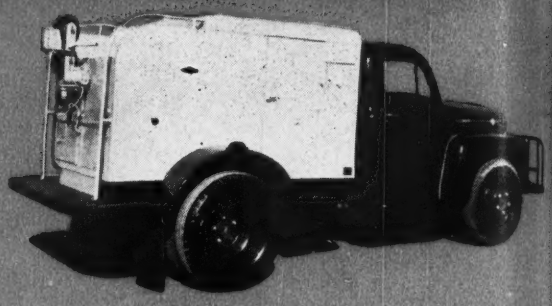

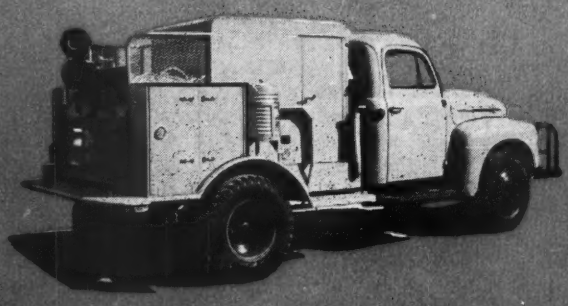

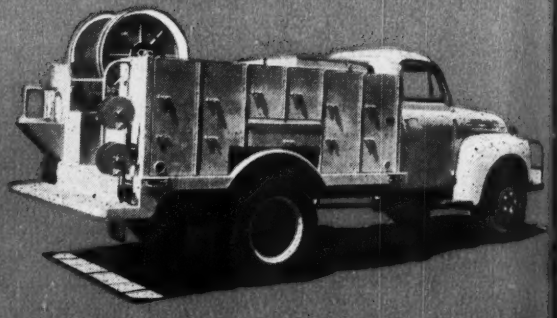

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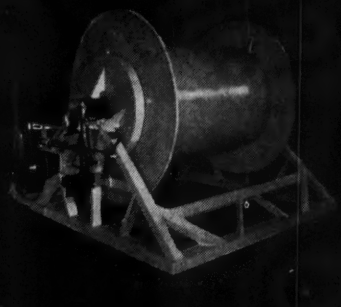

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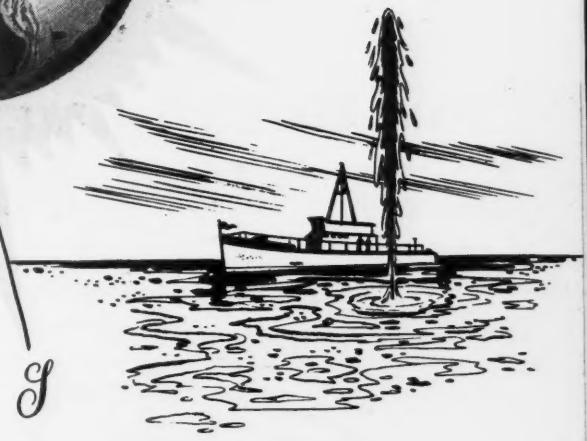

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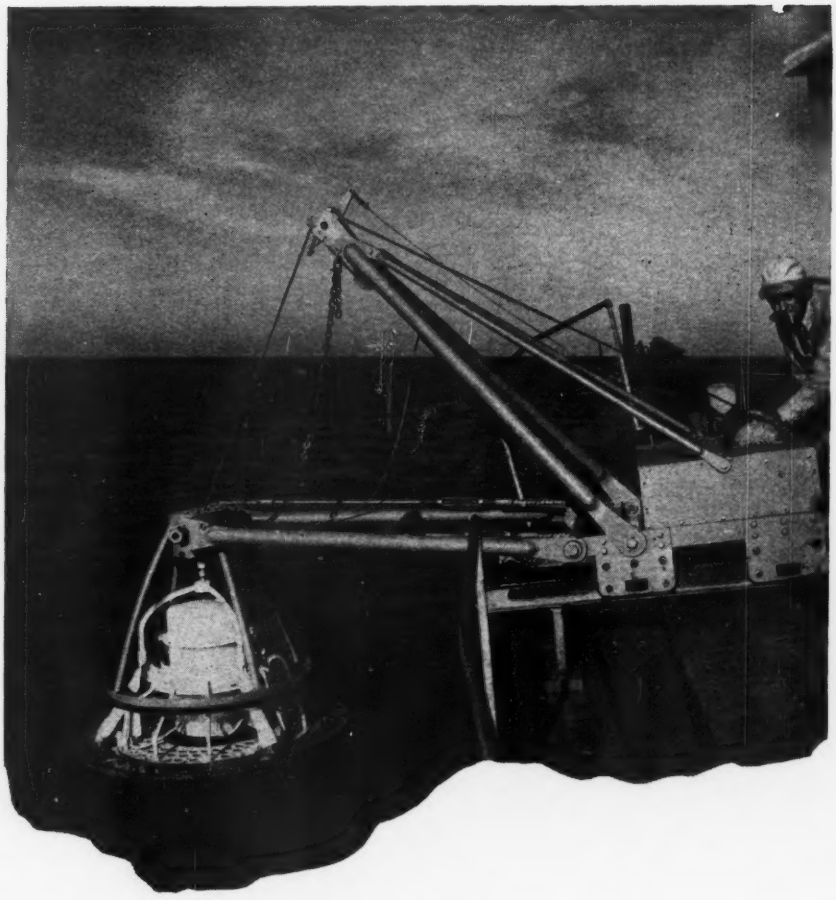

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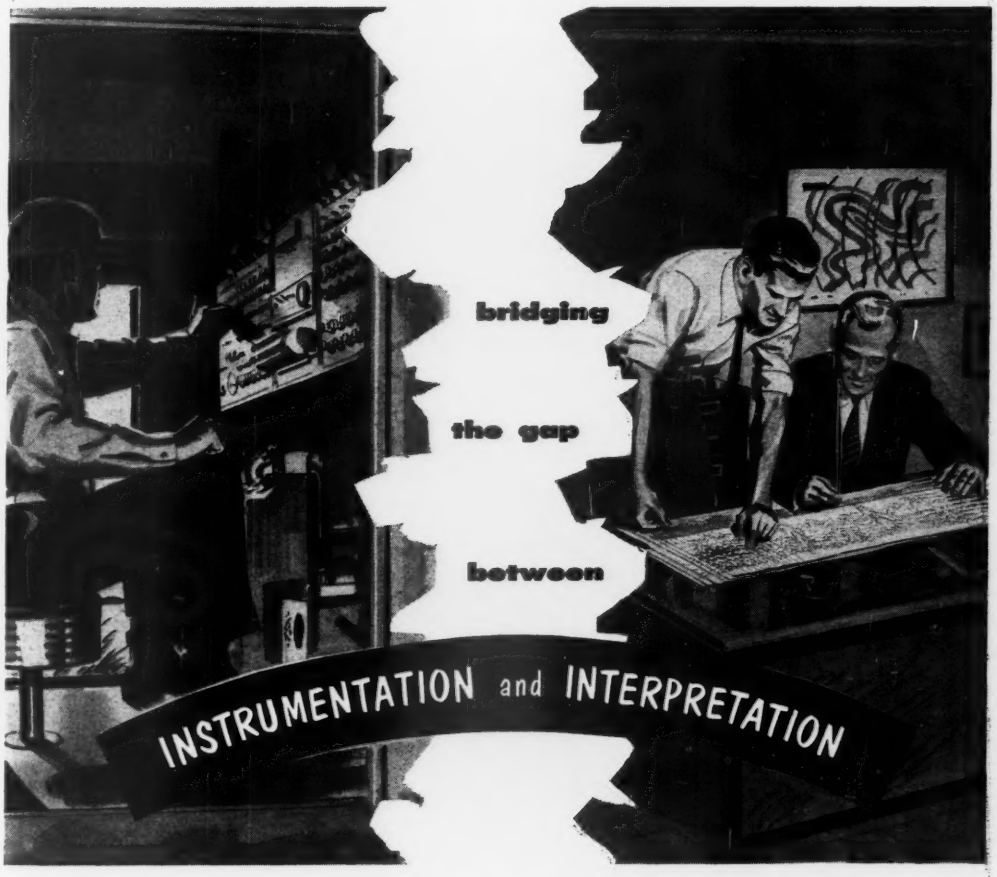

It is a known fact that geophysical instrumentation has advanced faster than geophysical interpretation. Due largely to the competitive efforts of specialized manufacturers, instrumentation has made significant strides in the past ten years. Whereas, interpretation has not kept pace.

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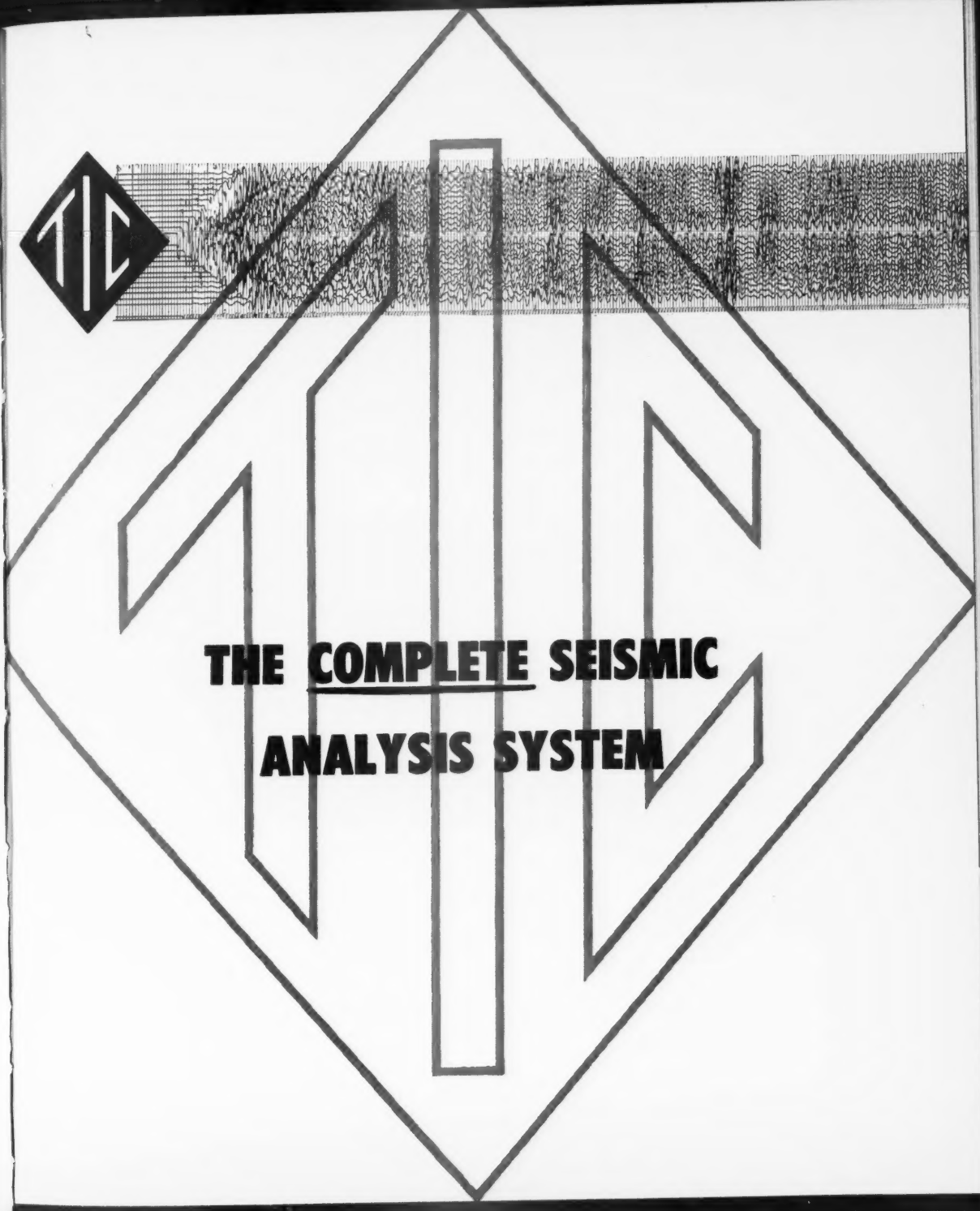

THE COMPLETE SEISMIC ANALYSIS SYSTEM

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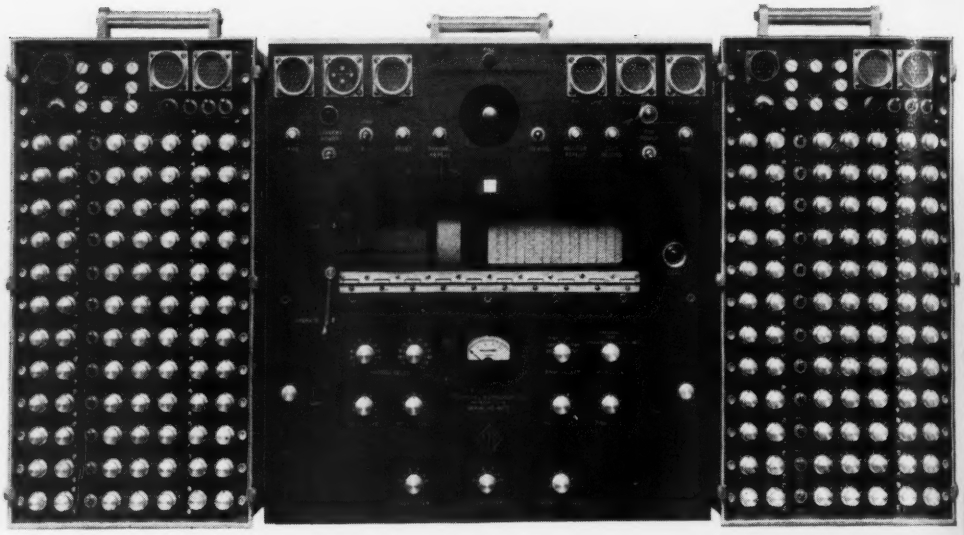

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Simultaneously records 28 signals on magnetic tape. Automatically sequentially scans each recorded channel and provides a permanent visual record for immediate inspection. Automatic shot control. Separate timing channel. Total time error less than one millisecond. Narrow magnetic tape. New Brush magnetic heads permit recording 28 channels on 2¼" tape. Minimum equipment requirement. Only one demodulator. Permanent monitor record eliminates need for photographic recorder in truck. Operates on truck batteries.

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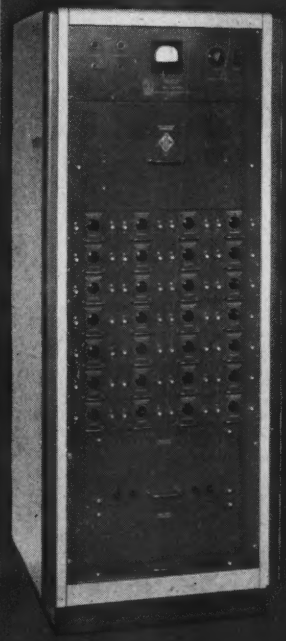


NEW REPRODUCER

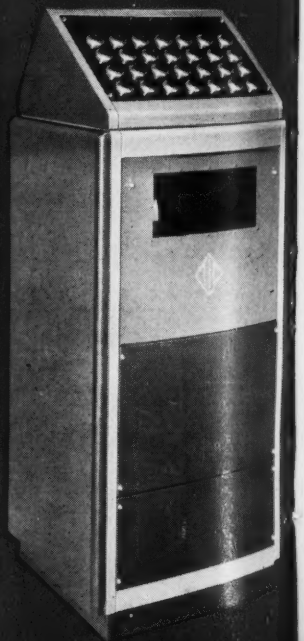
Supplies replica of original or corrected electrical signal which can be filtered or mixed and fed into a conventional photographic oscillograph or such special equipment as desired. Operates on 110 v AC.

NEW DEMODULATORS

Housed in same cabinet as Reproducer. Flat frequency response. High signal-to-noise ratio. Minimum harmonic distortion. Plug-in etched circuit construction. Operates on 110 v AC.

NEW COMBINATION FUNCTION GENERATOR-TRANSFER DRUM

Automatically scans field tape channel by channel and automatically inserts time corrections for weathering, shot-out, elevation, and offset in accordance with individual settings for each channel. Inserts velocity correction to put chart on depth, rather than time, coordinate. Corrected tape then used for any desired filter and mix analysis. The original tape is not affected and can be filed for future reference. Thus the utmost flexibility of operation is provided. Operates on 110 v AC.



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4) Complete re corrections in the ana lyzer, all requ inserted into final record. Corrects velocity.

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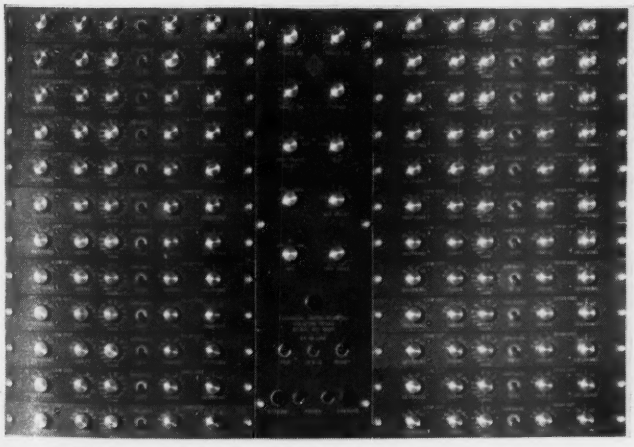

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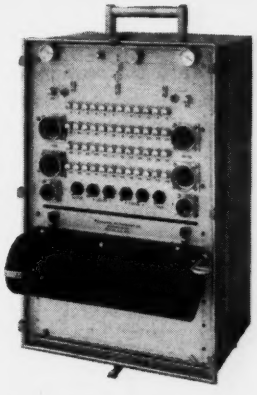
Works directly from output of Reproducer. Broad band seismic information is filtered and mixed as determined by operator and fed directly into conventional photographic oscillograph.

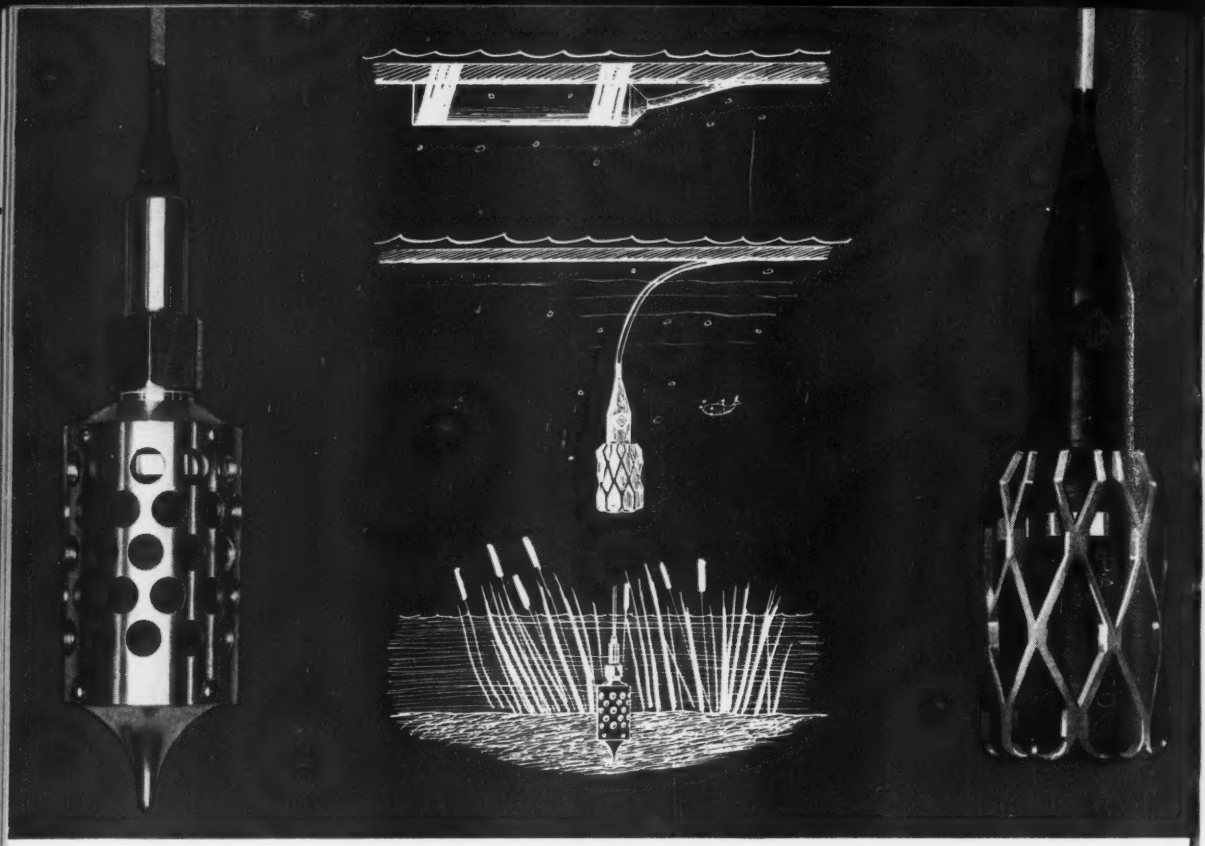
Filters: Three low and two high, each with 15 db attenuation. Six positions per filter. Each Position individually damped. Choice of use of any combination of filters.

Mixers: Many types mixing and compositing provided. Two-way and one-way available as standard. Percentage of mixing adjustable on front panel.



FINAL RECORD OSCILLOGRAPH

This field station Oscillograph records the final filtered and corrected record ready for the computer. Is available with from 25 to 50 traces on from 6 to 10 inch paper. Operates from 110 v AC or 6-12 v DC if preferred. Many other special and standard features may be incorporated if desired.



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4) *Flexibility*—Designed to be used in water, either hanging or taped, or in soft marsh, with only a screwdriver required as tool. Output impedance and other characteristics chosen for use in any combination of units per trace.

5) *Mechanical strength and stability*—Completely water-proofed and coupled to sea by rubber casing and protected mechanically by brass housing. Can be used at any reasonable depth where seismic exploration work will be conducted.

6) *Conventional response*—Designed to have response curve and characteristics similar to conventional 30 CPS dynamic phone.

7) *Proven results*—Have already provided good usable traces in areas previously considered non-record or poor record areas using other phones.

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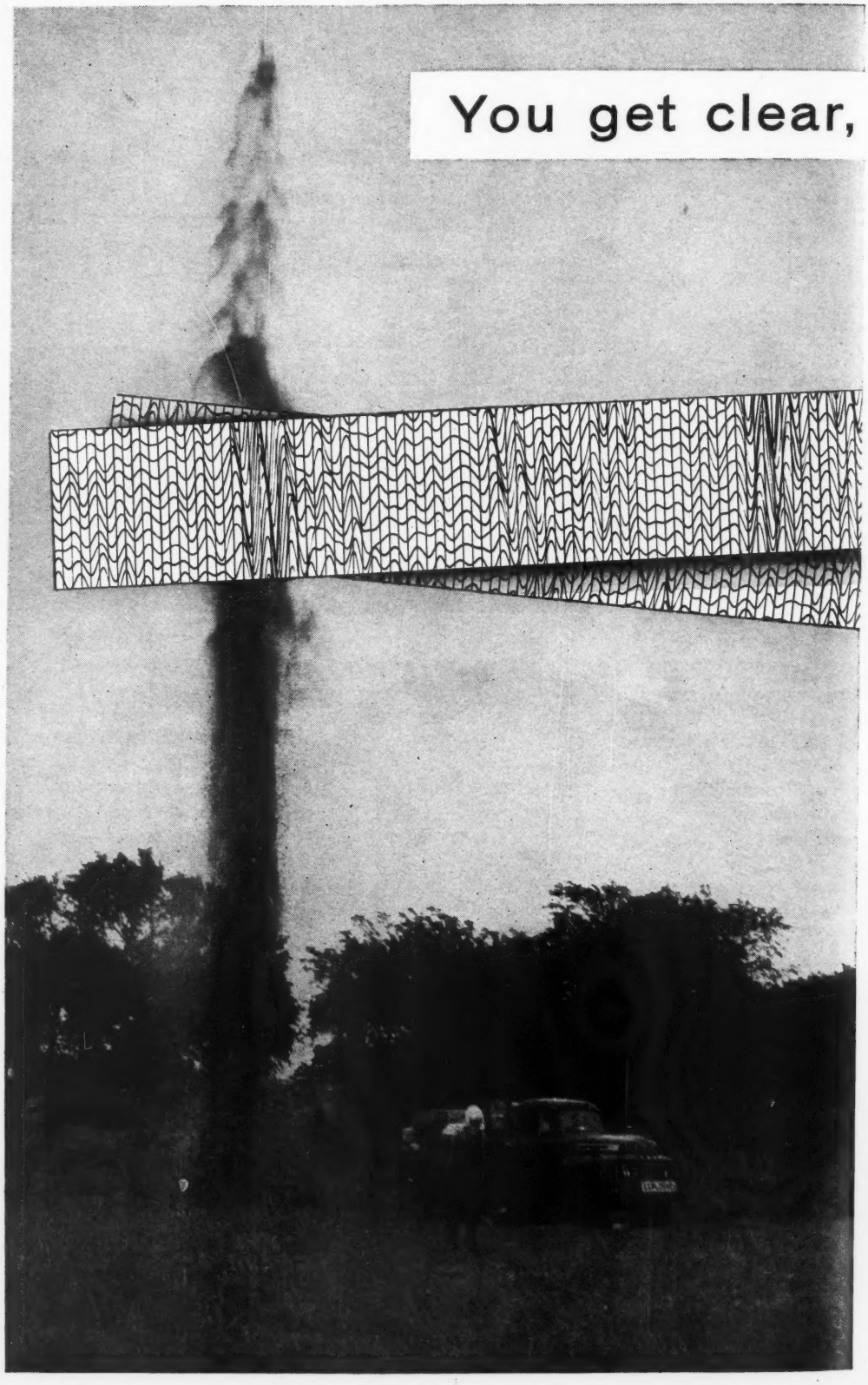
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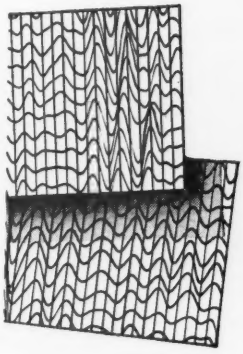

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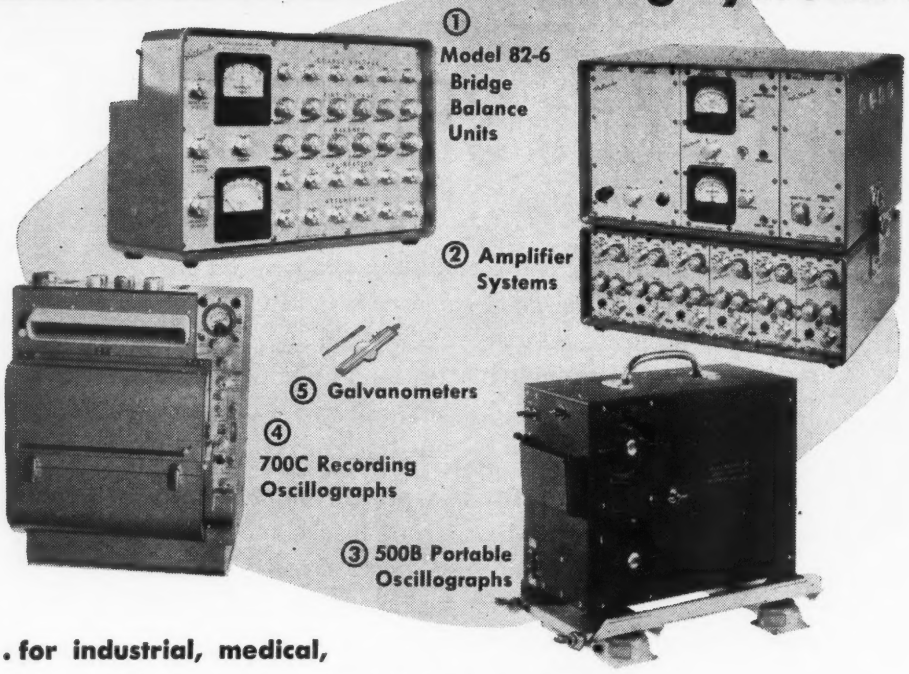

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1 **The Heiland Model 82-6** six channel bridge balance and strain indicator unit provides a simple and accurate means of calibrating, measuring and controlling static and dynamic current phenomena from resistive type transducers in connection with oscillographic recording.

2 **The amplification** of static and dynamic current phenomena for oscillographic recording is simple and accurate when the highly-stable Heiland Model 119 Carrier Amplifier System is used in conjunction with the Heiland recording oscillograph. For resistive, variable reluctance, and differential transformer type transducers. Provides high amplitude oscillograph recordings having a flat respouse to 1000 cps.

3 **The 500-B is convenient** for mobile applications where portability and ease of operation are essential. For recording up to 12 separate phenomena. Small in size and easy to operate, the takeup magazine construction of the 500-B permits the taking of short individual records as well as one continuous record 100 ft. long.

4 **The Heiland 700-series Oscillographs** afford complete accessibility from one operating surface and require only a minimum of space for either table or rack mounting without modification. Features include paper speeds from 0.030 to 144"/sec., daylight loading with separate light-tight takeup and supply drums, and trace velocity to 30,000 inches per second on No. 809 recording paper.

5 **The Series "M" Sub-miniature Galvanometer** is the most advanced design and is a natural complement to the new 700-series oscillograph. Maximum zero stability, great sensitivity, and ease of adjustment are among its outstanding features.

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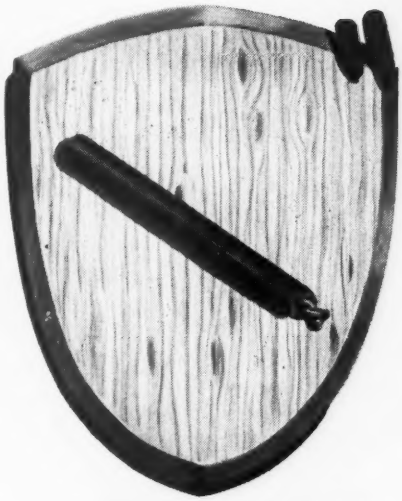

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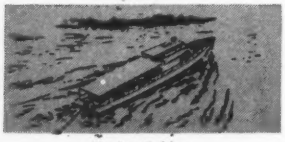

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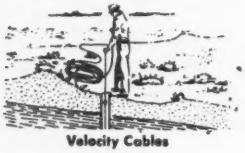

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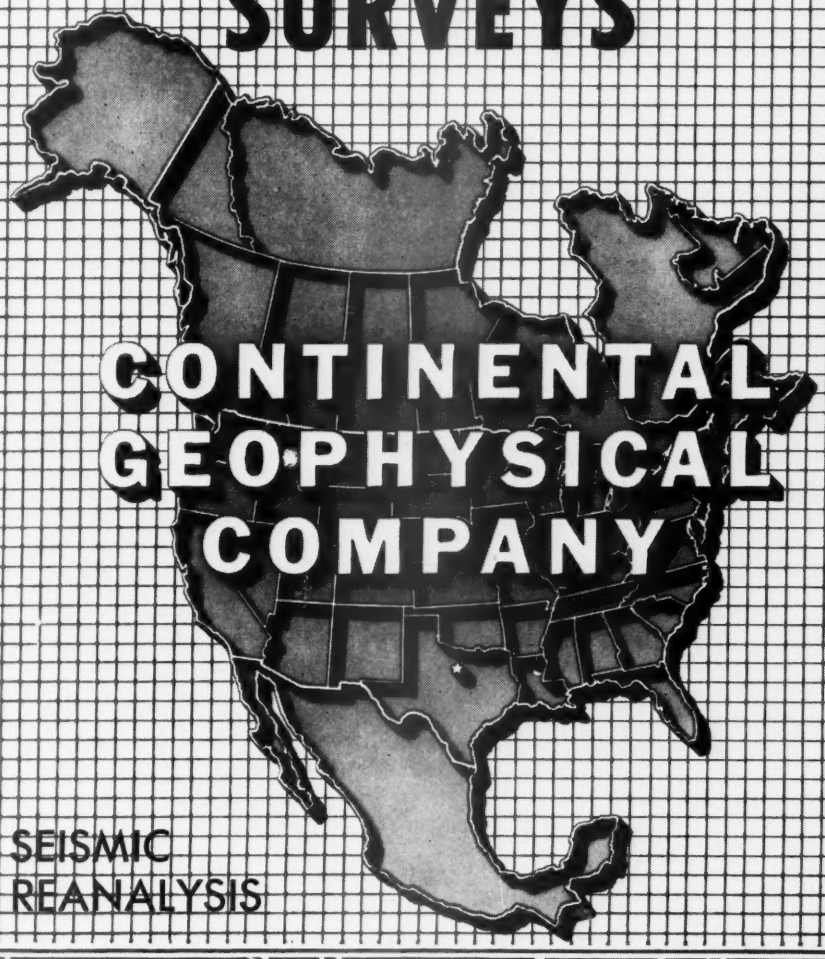

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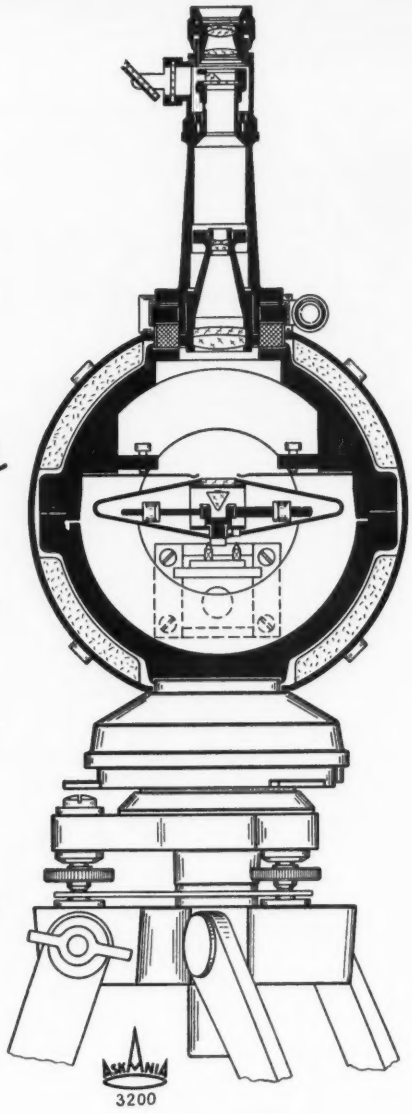

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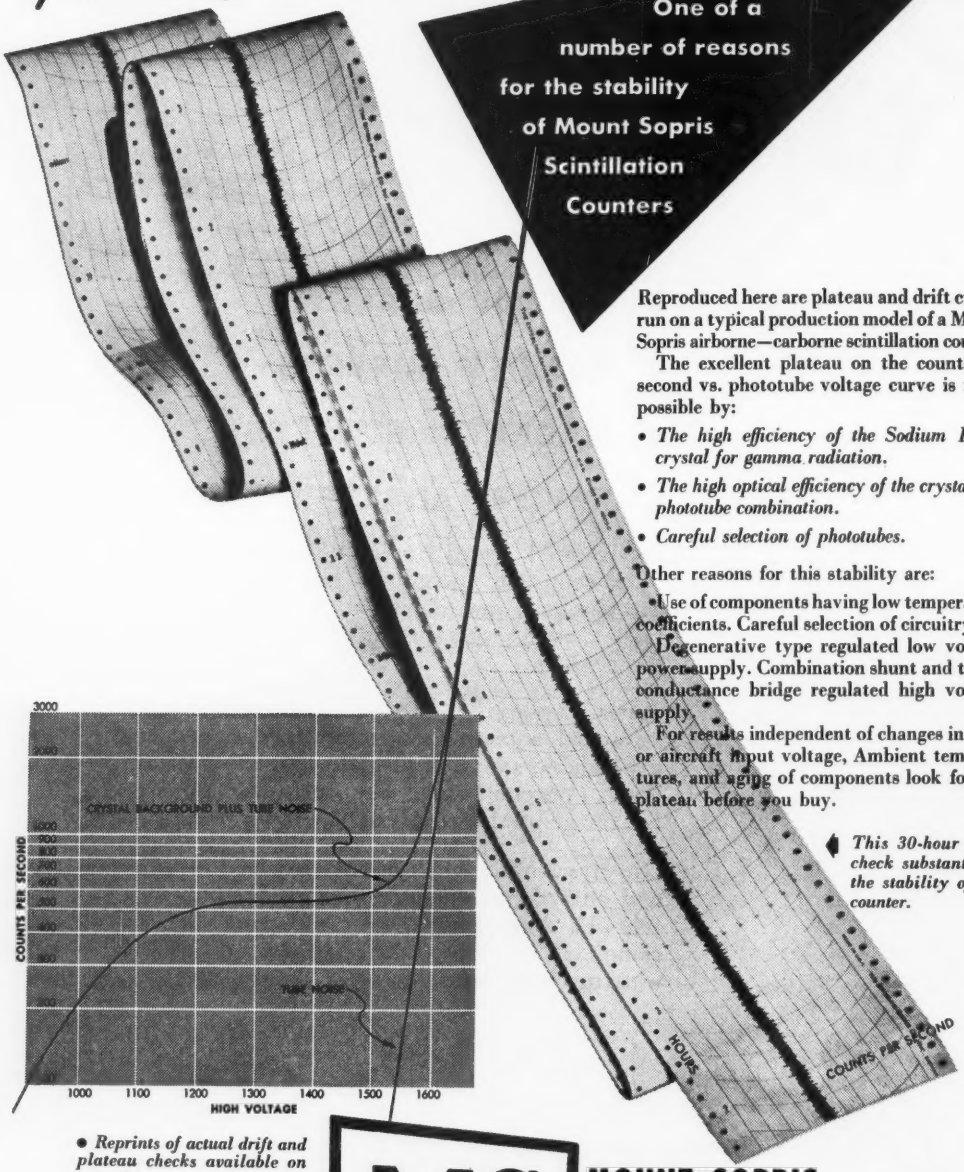

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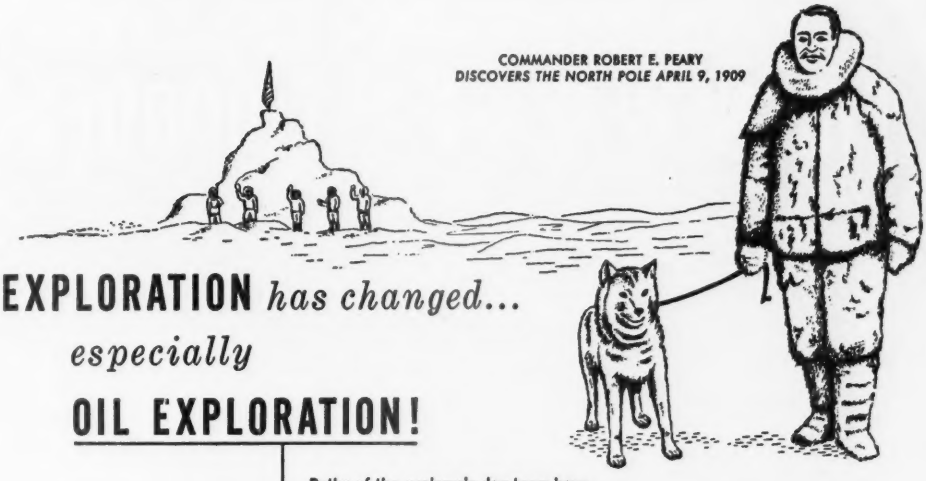

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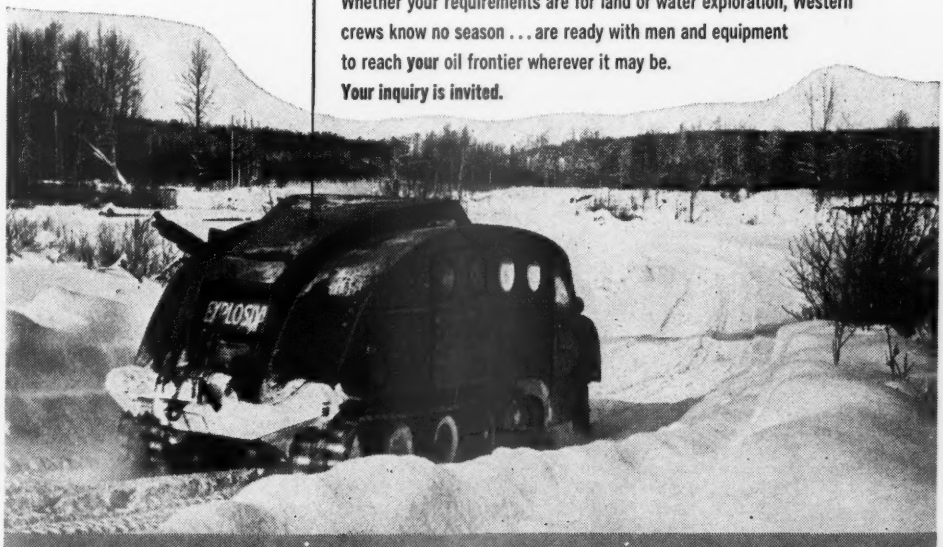

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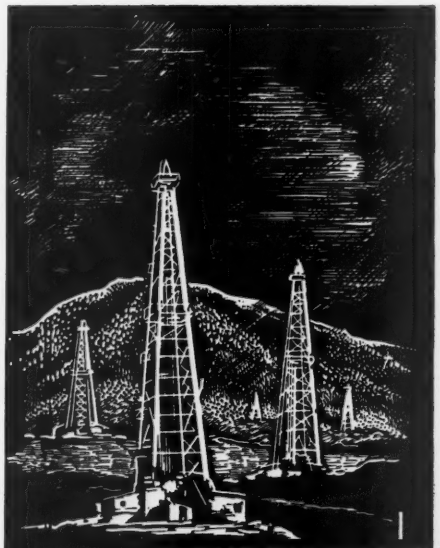

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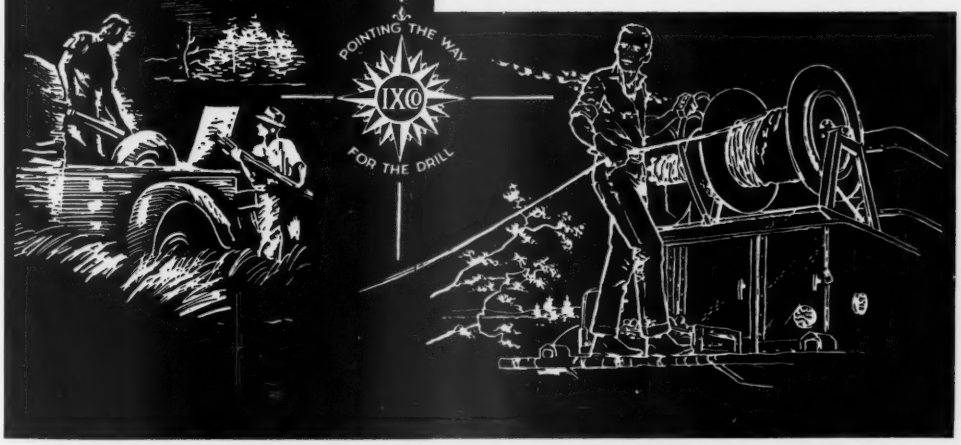

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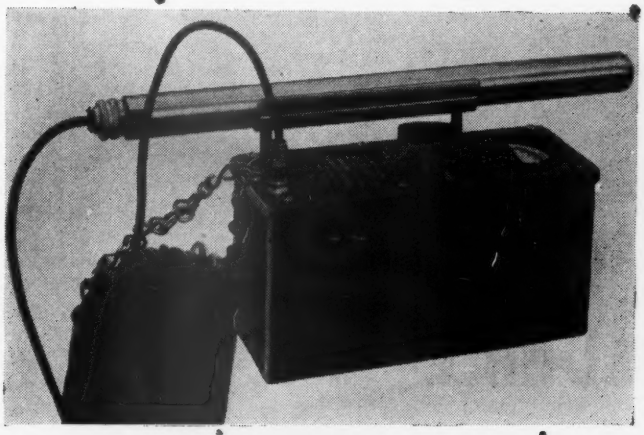

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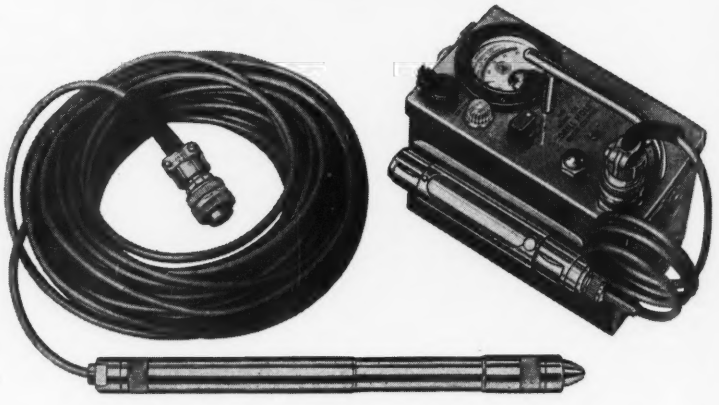

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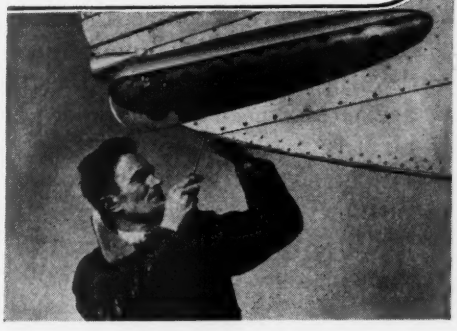

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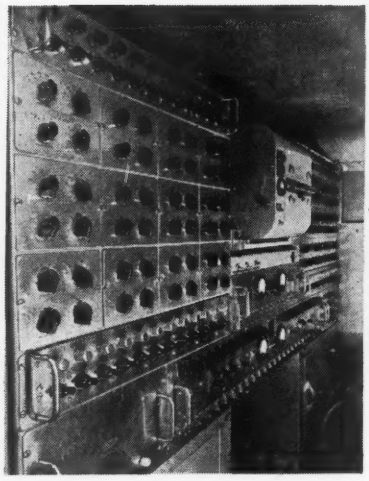

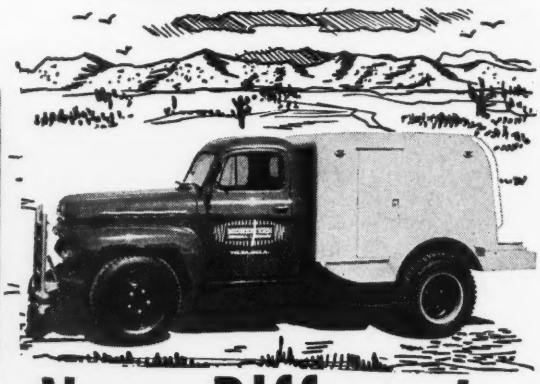

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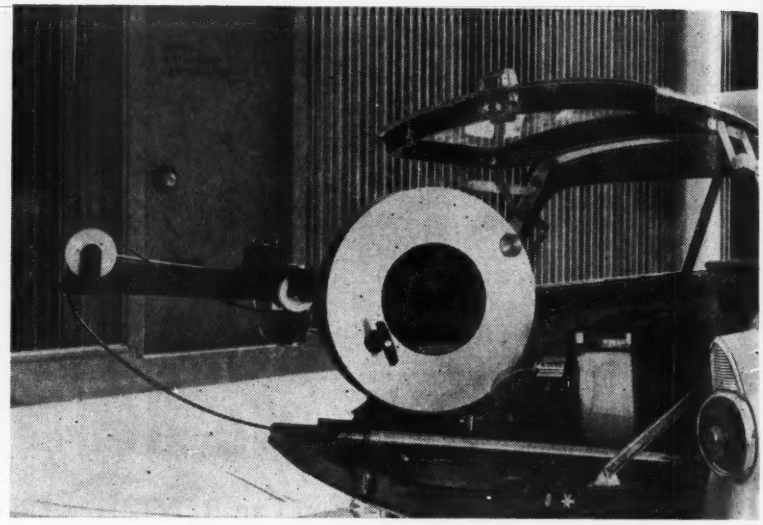

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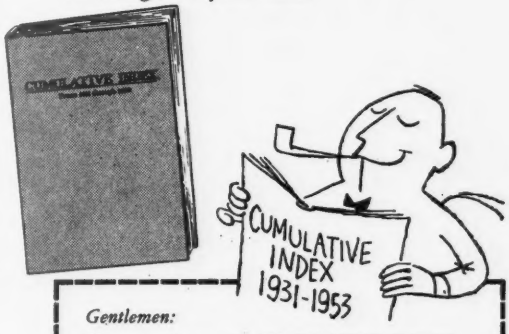
Filbert was buried under a ton of detail — and every ounce of it urgent — when the boss stormed in with the old Poppy Field on his mind. There was a case history on that field . . . came out around 1932, he thought . . . find that paper, Filbert. And, Filbert, find it by five o'clock. Understand, Filbert?

Filbert stared blankly into space. A dull film clouded his eyes. Surely, with luck, he would be dead in five minutes. But visions of his widowed wife and fatherless children pulled him to his feet and sent him trudging out the door . . . to the library.

It would take all day. He'd be spending valuable time his company could hardly afford. And he'd be using all his exploration skill to locate that blessed paper — not to mention structures . . . Filbert stopped at a drug store and bought $4.00 worth of aspirin.

Had Filbert spent that $4.00* on the CUMULATIVE INDEX, he would have saved himself that headache and many, many more. The S.E.G. CUMULATIVE INDEX 1931-1953 is a complete library on geophysical data at the tips of your fingers. Remember, a man is as useful as the knowledge he possesses. The CUMULATIVE INDEX is knowledge on your desk!



Gentlemen:

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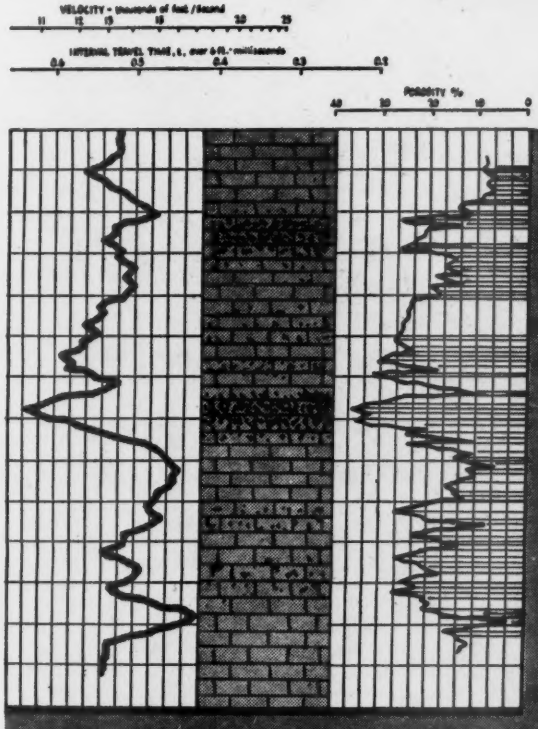
EXAMPLE: CORRELATION OF A CONTINUOUS VELOCITY LOG AND THE POROSITY OF A LIMESTONE FORMATION


VELOCITY - thousands of feet / second
11 12 15 18 20 25
INTERVAL TRAVEL TIME, t, over 6 ft. - milliseconds
0.6 0.5 0.4 0.3 0.2
POROSITY %
40 30 20 10 0

The data shown here are the results of a test conducted by Magnolia Petroleum Company to demonstrate the natural relationship between interval velocity and the porosity of a limestone.

For this test, a section of limestone was sampled for porosity, and the values recorded, *see curve on right.* An interval velocity log was then made of the same limestone section, *see curve on left.* Note the marked similarity of the two logs.

Continuous Velocity Logging is a method of determining the *"soundness"* of rock by measuring its interval velocity. Investigate Continuous Velocity Logging today. Write for complete information or call the nearest SSC Office.

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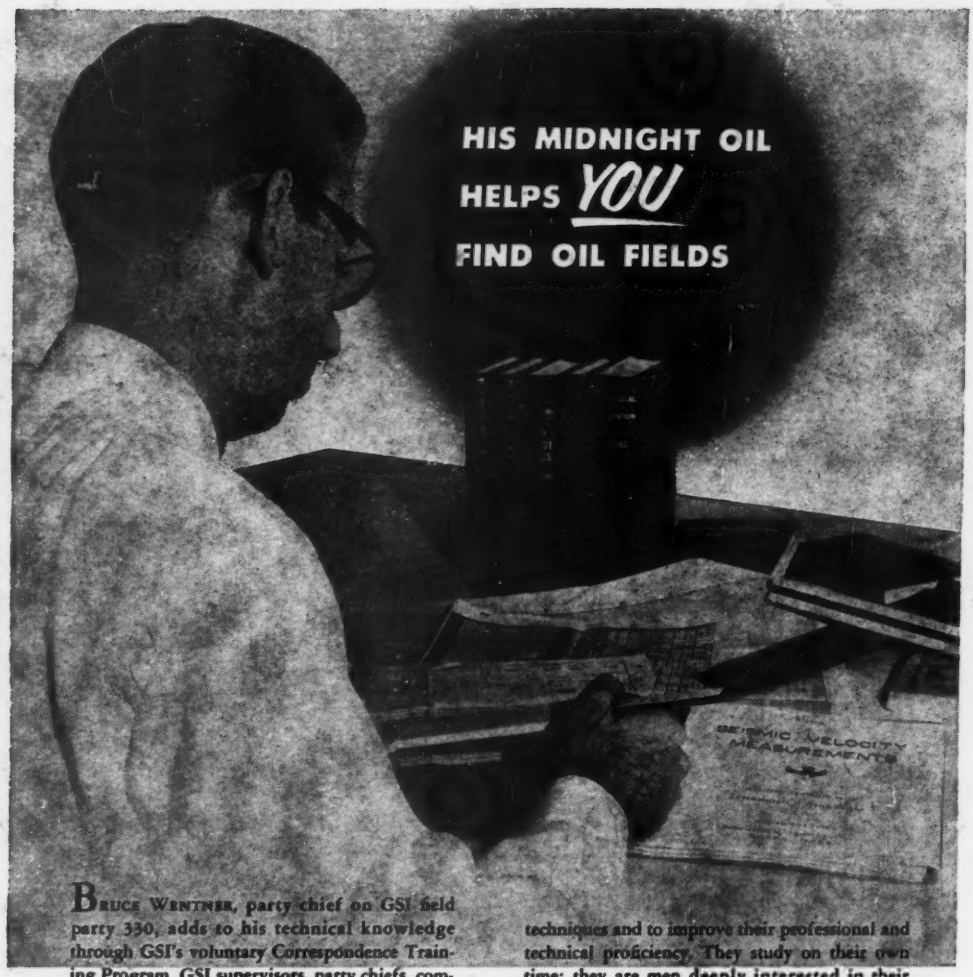

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